Heliyon 10 (2024) e40364

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

# Design of intelligent human-machine collaborative robot-assisted craniotomy system

Meng Cui [a,*,1], Wenqing Ren [b,1], Tengfei Cui [c,1], Ruifeng Chen [a,**], Yi Shan [a,***], Xiaodong Ma [b,****]

[a] Department of Emergency Medicine, The Sixth Medical Center, Chinese PLA General Hospital, Beijing, 100048, China
[b] Department of Neurosurgery, The First Medical Center, Chinese PLA General Hospital, Beijing, 100853, China
[c] Institute of Intelligent Robotics, Beijing Institute of Technology, Beijing, 100081, China

ARTICLE INFO

*Keywords:*
Medical robotics
Craniotomy
Human-machine collaboration
Image-guided surgery

ABSTRACT

*Objectives:* To develop an intelligent human-machine collaborative control robot-assisted craniotomy system, and test its efficacy by experiments.
*Methods:* The system integrated a UR5 robotic arm (Universal Robots, Denmark), a host computer, a double six-degree-of-freedom force sensor(Nanjing Yuli Instrument Co., Ltd.), a medical drill (AESCULAP®, Germany), a Polaris Optical navigation system(NDI,Canada), with a self-designed navigation procedure and a visual graphical user interface(GUI). According to a preoperative CT and resection plan, the motion of robotic arm can be restricted in a precise and safe area. Through experiments of the 3D-printed skull models and animals (Bama mini pig), we tested the accuracy, efficiency and safety of the robot system.
*Results:* After successfully developed the robot-assisted craniotomy system, we tested the collaborative controlling fluency of robotic arm with the average response time less than 1 s, as well as feedback sensitivity of force sensor with an average result of 60 N and 50 N when drilling on skull models and mini pigs respectively. In addition, compared with “surgeon” group, “robot” group had less average positioning error (1.87 ± 0.66 mm VS 3.14 ± 0.73 mm, $P < 0.001$) and time spent (6.64 ± 1.15min VS 8.06 ± 1.10min, $P = 0.001$) in skull model experiments. Also, in mini pig experiments, “robot” group had less average positioning error (3.26 ± 0.51 mm VS 4.39 ± 0.75 mm, $P = 0.008$) and time spent (11.83 ± 0.92min VS 26.10 ± 1.62min, $P < 0.001$) compared with “surgeon” group. No matter in skull model experiments or in mini pig experiments, the durations of robot startup and navigation process were not different between the experimental group and control group (3.44 ± 0.98 VS 3.75 ± 1.00min, $P = 0.39$ [skull model experiments]; 6.42 ± 0.65 VS 7.10 ± 1.12min, $P = 0.11$ [mini pig experiments]). Because of limited samples, we compared the incidence of tissue injury between “robot” and “surgeon” group jointly (3.8 % [1/26] VS 19.2 % [5/26], $P = 0.193$).
*Conclusion:* Successfully developed, the human-machine collaborative robot-assisted craniotomy system achieved craniotomy procedure fluently providing a sensitive force feedback to surgeon

* Corresponding author.
** Corresponding author.
*** Corresponding author.
**** Corresponding author.
*E-mail addresses:* mcmeng182@163.com (M. Cui), cc_rrff@126.com (R. Chen), nghicu@163.com (Y. Shan), xiaodongm@hotmail.com (X. Ma).
[1] These authors contributed equally to this work.

https://doi.org/10.1016/j.heliyon.2024.e40364
Received 25 August 2024; Received in revised form 11 November 2024; Accepted 12 November 2024
Available online 13 November 2024
2405-8440/

and did better than manual work by surgeon in accuracy, efficiency and safety. Further experimental research needs to be performed to testify its applicability in neurosurgery in future.

## 1. Introduction

Robot-assisted neurosurgery appeared in 1980s. Traditional neurosurgery robots are mostly used in stereotactic surgery [1–3], such as the Neuromate made in France [4], the NeuroArm made in Canada, and the CRAS robot system [5,6] as well as Remebot surgical robots jointly developed by Beijing University of Aeronautics and Astronautics and Chinese Navy General Hospital [7]. Craniotomy robot, whose main task is drilling and milling the skull precisely, is very different with traditional neurosurgery robot. Based on early neurosurgery robots, RobaCKa and CRANIO systems developed in Germany and Neuromate-based hybrid robot system developed in the United States can perform craniotomy [8–10], but all of them were still in the stage of experiment, and their accuracy and safety needed to be improved [11–13]. In recent years, Chang Gung University in Taiwan had developed the navigation-guided robotic arm drilling system, University of Utah in USA had developed the computer-aided design surgical drilling system; Both of these robotic arms can only move automatically according to a motion trajectory planned, furthermore the lack of force feedback and collaborative control caused their danger in use [14].

The manual craniotomy takes time and efforts of surgeons, and its accuracy, safety and efficiency need to be improved. The robot-assisted craniotomy system has the following advantages: 1) Position of robotic arm is guided by image navigation system, which makes the positioning more accurate. 2) Robotic arm has a good stability and more precise force control than human and it can

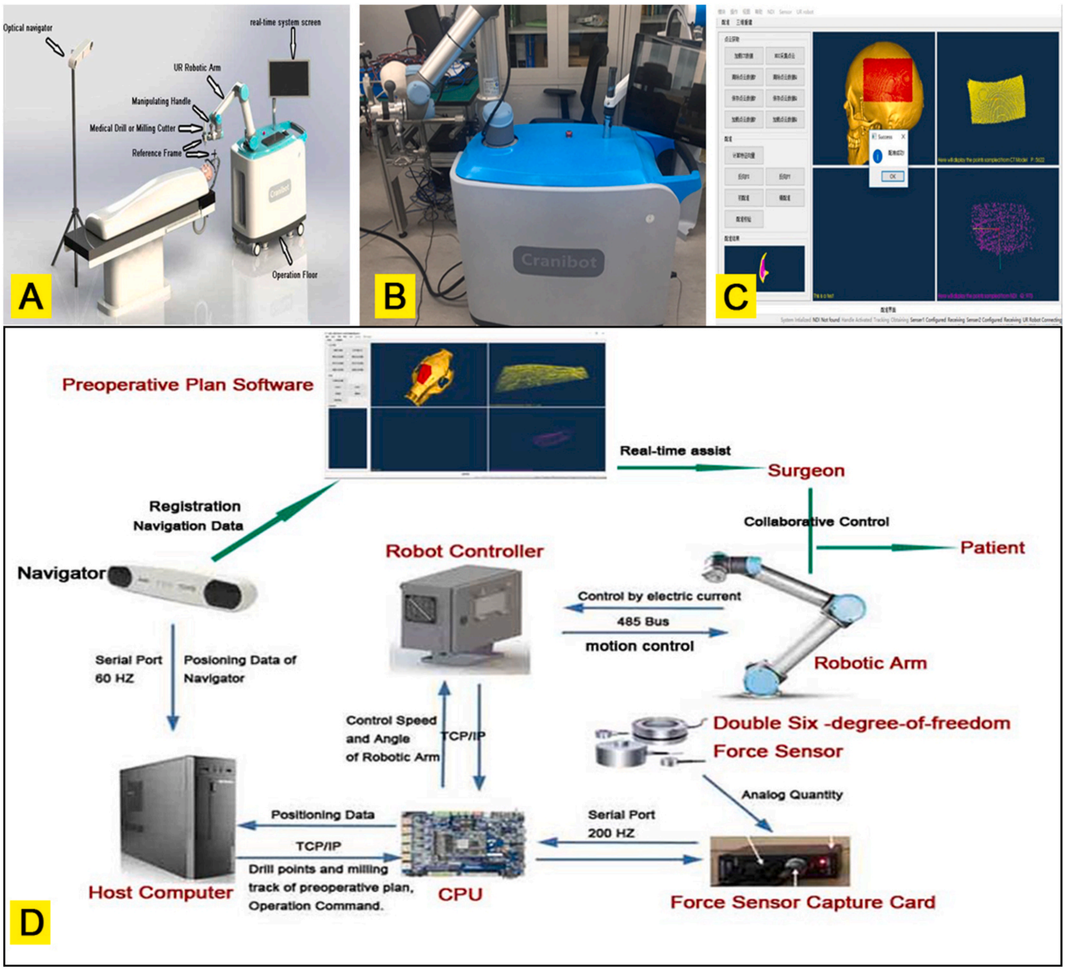


**Fig. 1.** Composition of Robot-assisted craniotomy system and work flow. A: Schematic diagram of the main hardware composition. B: Physical map. C: Preoperative plan and registration between preoperative CT data and intraoperative data of skull scanned by positioning probe. D: Workflow overview of the robot system. Through the navigation system, preoperative planning software, real-time visual display aid, force feedback, robotic arm motion controller, the system achieved human-machine collaborative control.

eliminate the shaking risk of hand, which makes it more secure and reliable. 3) The stable and fast working mode of robot can improve the efficiency of craniotomy, and the precise positioning of it can reduce the damage of intracranial tissues. 4) Human-machine collaboration enables robot to break through the obstacles of full-automatic control, which can reduce the risk of fully automatic operation and exert the flexibility of human.

Considered the advantages above, we had designed and developed the intelligent human-machine collaborative robot-assisted craniotomy system named Cranibot jointly with Institute of Intelligent Robotics in Beijing Institute of Technology, then tested its accuracy, safety and efficiency through experiments.

## 2. Methods

### 2.1. Hardware and connection

The hardware integrated a six-degree-of-freedom (six-Doff) UR5 robotic arm (Universal Robots, Denmark), liftable robot operating platform (base), a host computer, a double six-DoF force sensor(Nanjing Yuli Instrument Co., Ltd.) [15], a medical drill (AESCULAP®, Germany), a Polaris Optical navigation system (NDI, Canada) (Fig. 1A–C).

As was proved previously in the experimental field of medical robots, the six-DoF UR5 robot had the good man-machine interaction characteristics, system stability and programming scalability, so it was chosen for this system. The connection of the entire hardware was based on the connection of the robotic arm and the medical drill system (a drill or milling cutter connected by the universal interface in the end of robotic arm), which realized the mechanical and spatial position control of medical drill and milling cutter by robot. The robot arm can be covered with a disposable sterile film in surgery. The drill and mill was sterilized before they were connected to the end of robotic arm. The end of robotic arm can also be covered with the disposable sterile film after the connection finished. To meet the requirements of light weight of this system, lightweight aluminum alloys and Acrylonitrile Butadiene Styrene (ABS) materials were used as supporting materials and shells and the load-designed manipulators were designed. After the assembly of robotic arm, console, housing, and universal interface device of operating terminal was completed, the overall optimization of the robot components was finally achieved. As a result, the inertia of the robot and friction between devices were reduced to ensure safety of both manual and cooperative modes. The motion of robotic arm was controlled by a control host through an independently developed program software.

The navigation system mainly included the Plorias infrared optical navigation device (NDI, Canada), positioning reference frame and positioning probe. Two positioning reference frames were separately installed on the head holder and the end of robotic arm, which can track the position and attitude of head and robot.

### 2.2. Software

The software used a self-designed navigation and positioning program and a visual graphical user interface [16]. The preoperative plan and design software were designed by the Zhongke Wahe (Beijing) Technology Company. The initial registration of navigation was performed based on principal component analysis (PCA). The data of point clouds was obtained from both preoperative brain CT and skull scanning with a laser scanner. The feature vectors of point cloud of both groups can be obtained and matched by PCA. The precise registration was performed by iterative closest point (ICP) algorithm based on kd-tree search [17,18]. The ICP algorithm achieved to find a set of points ($\{P_i^k\}, i = 1, 2 \ldots N_x$) which can matched all points of the reference point set P ($\{p_i\}, i = 1, 2 \ldots N_p$) (obtained from preoperative brain CT) with those of measurement point set Q ($\{q_i\}, i = 1, 2 \ldots N_q$) (obtained from skull scanning). The transformation matrix (from P to $\{P_i^k\}$) that had the minimum error was calculated. The $\{P_i^k\}, i = 1, 2 \ldots N_x$ was the nearest point from point set P to Q. By continuously searching for the nearest point from the reference point set P and calculating the transformed cloud of points P, we achieved precise registration of P and Q.

At the same time, an active constraint-based security interactive collaborative interactive control algorithm was designed to implement security threshold control in force perception and control. The interactive collaborative interactive control of the robot included the control of surgical instrument feedback force the surgeon's operating force. We constructed iTaSC control frame which was a speed based control method. Four position coordinate systems were defined on the base of robot, two six-DoF force sensors and the handle on the end of robotic arm. Another coordinate system was also defined, it can be changed with the change of the origin position, which is the contact point between the end of robotic arm and the environment. The control input of the system is the speed of the contact point. This speed was decomposed into the speeds of each joint of the robot using an inverse kinematics solver so that the motion of robot can be controlled. Furthermore force of drill and mill task can be decompose based on force/position hybrid control, the motion space of robotic arm can be limited in a safe area based on the impedance control.

### 2.3. Workflow of the system

After the robot and software were started, the preoperative CT data was loaded to perform three-dimensional image reconstruction of the skull that was fixed on a dedicated head holder. When the scalp and subcutaneous tissue were incised, we fully exposed the target skull and selected the registration area on the operator interface of screen, then saved and loaded the data of cloud composed of points [19]. The skull was scanned with a navigation probe or laser scanner to obtain another cloud of points of the skull surface by using optical navigation system [20,21]. Then after we clicked "Load cloud of point's data Q″, the computer calculated the feature vectors of the two groups of clouds of points. According to the location of the drilling, directions of the feature vectors were adjusted and the method of using a standard matching point to register was applied to perform initial registration [22]. After that precise registration was completed. According to the position of intracranial lesions, drilling points were selected by surgeon on the screen of interface of 3D reconstruction skull and trajectory of milling was generated automatically by preoperative planning software. A surgeon manipulated the handle on the end of the robotic arm to perform craniotomy. During the whole craniotomy process, multi-security interaction (including interactive collaborative control by surgeon and robotic arm, interactive control by robotic arm and operation environment such as patient) was achieved through virtual display on screen, active constraint-based security algorithms, and high-precision force feedback provided by six-DoF force sensor (Fig. 1D) [23–26].

### 2.4. Model and animal experiments

Eight 3D-printed PVC skull models and five Bama mini pigs were numbered respectively. Pigs were provided by the Animal Experiment Center of Chinese PLA General Hospital, license number: SYXK (Military) 2017-0017. Ethical approval was authorized by the Animal Experiment Welfare and Ethics Committee of Chinese PLA General Hospital, the ethics approval number was 2017-D12-55.

Each subject was performed craniotomy symmetrically (two parts on the left and tow symmetric parts on the right of the skull, each

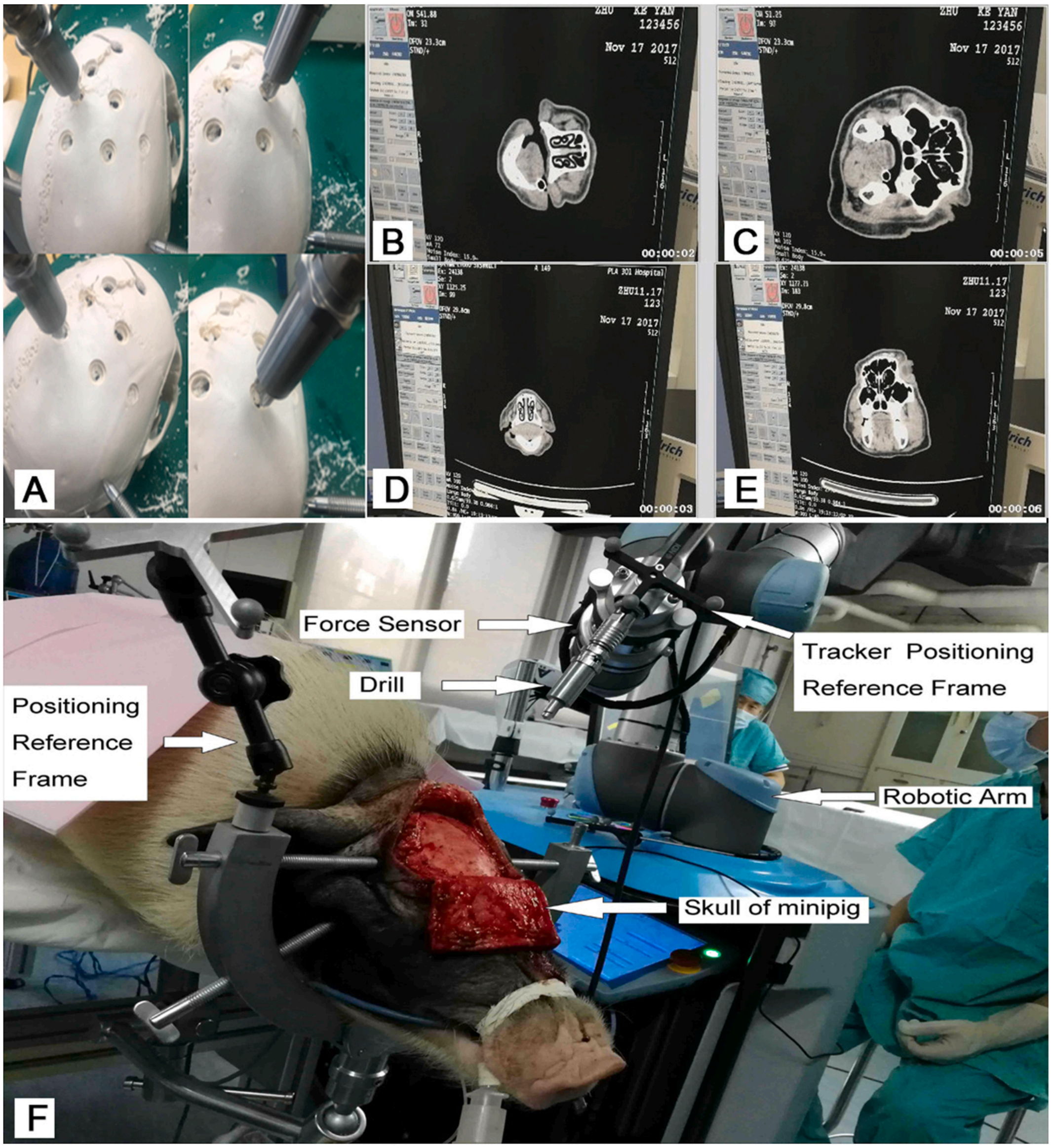


**Fig. 2.** A shows the experiments of PVC skull models. B and C show the preoperative CT images of mini pig, D and E show the post-operative CT images, no tissue injury or hemorrhage was detected after craniotomy by robot system. F shows the experiment of mini pig.

part had 4 drilling points, which formed a square bone window after being drilled and milled). One part was selected randomly as the experimental group (performed by robot), the symmetric part on the other side was the control group (performed by the same surgeon manually). In order to avoid the influence of surgeon' fatigue on the accuracy of experimental results, the surgeon had a rest for 30 min after each part of craniotomy completed. Because of the symmetry of skull, the "robot" group and "surgeon" group had same experimental conditions except the craniotomy methods, so all the experiments can be seemed as paired design (Fig. 2A and F). We recorded changes of force feedback and the positioning errors (the average of the difference in position error between 4 actual drilled points of each square bone window and 4 points of preoperative plan), time spent and the incidence of tissue injury such as dura tear (The tissue injury was detected by intraoperative finds and CT images comparison of pre- and post-operation) (Fig. 2B–E). The total duration time of craniotomy included process of setting up the robot system and navigation, as well as the craniotomy surgery (drilling and milling). The detail robot-assisted craniotomy process was showed in Fig. 3. Due to the limited sample sizes of models and animals, total incidence of tissue injury was calculated to compare the difference between "robot" group and "surgeon" group.

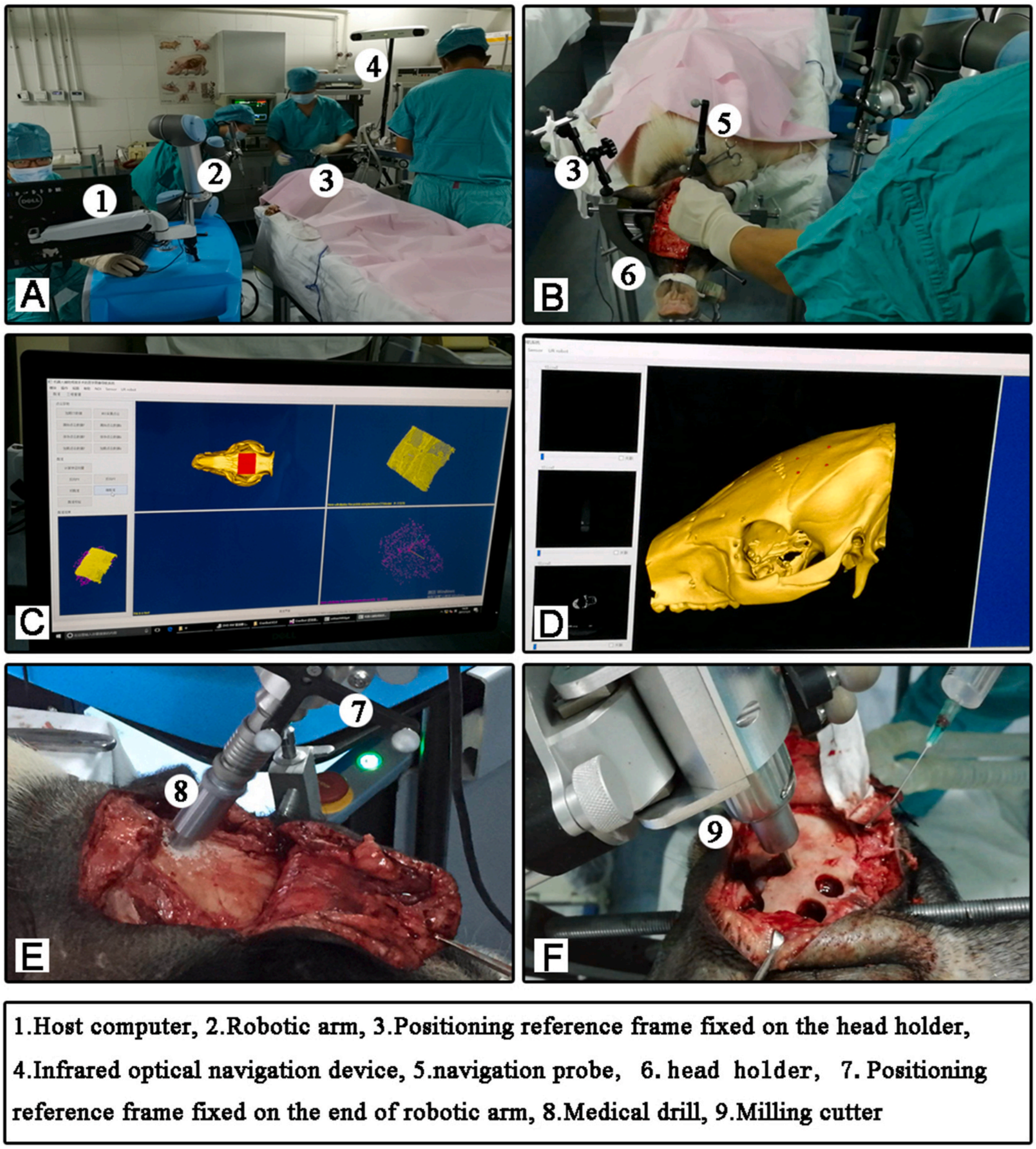


**Fig. 3.** Detailed robot-assisted craniotomy process. A. Startup of robot system and navigation. B. Navigation registration by scanning the skull of pig with a navigation probe. C. Skull reconstruction on the screen after precise registration. D. Choosing points of drilling and trajectory of milling on the preoperative plan software. E. Drilling process. F. Milling process.

### 2.5. Statistical analysis

SPSS 20.0 was used for statistical analysis. Shapiro-Wilk normality test was used to assess the normal distribution of measurement data, then the data of normal distribution was described by mean ± standard deviation($\overline{x}$ ± sd), the position error and time spent of experimental group and control group were compared by using student *t*-test of paired design. Counting data was showed as percentage, the comparison of incidence of tissue injury such as dura tear between experimental group and control group was made by calibration Chi-square test. $P < 0.05$ was defined as statistically significant.

## 3. Results

### 3.1. Results of force feedback

The robot had a good collaborative controlling fluency with the average response time less than 1 s.

The maximum feed forces ($F_{max}$, feeding force artificially pressed on the robotic arm) required in drilling of skull models and mini pig heads were 60 N (N) and 50N respectively. During milling, the contact forces of the milling cutters in the two experimental subjects were kept about -2N. A sudden change of torque was detected when the skull was drilled through.

### 3.2. Results of experiments

The position error and the time spent in experimental group and control group were shown in Table 1 (all the data followed normal distribution by Shapiro-Wilk normality test), which indicated that the position error and time spent of craniotomy in control group were greater than experimental group for both model and animal experiments, the differences were statistically significant (all of $P < 0.05$). While no matter in skull model experiments or in mini pig experiments, the durations of robot setting up and navigation process were not different between the experimental group and control group ($P > 0.05$). No matter in skull model experiments (3.20 versus 4.32 min, $P = 0.001$) or in mini pig experiments (5.41 versus 19.00 min, $P < 0.001$), the experimental group took less time in the craniotomy surgery (drilling and milling) than the control group.

For the skull model experiment, the incidence of tissue injury in the experimental group and control group were 6.3 % (1/16) and 18.8 % (3/16) respectively. For Bama mini pig experiments, the incidence of tissue injury of the experimental and control group were 0.0 % (0/10) and 20.0 % (2/10). The total incidence of tissue injury in the experimental group and control group for the two experimental subjects were 3.8 % (1/26) and 19.2 % (5/26), and there was no significant difference between two groups ($\chi^2 = 1.696$, $P = 0.193$).

## 4. Discussion

Although a craniotomy robot had been researched previously, it used closed-loop conductance-based feedback to perform automatic drilling and milling without image navigation; In addition, it only performed experiments on mice, so its efficacy and safety needed further test [27]. Among the research of RobaCKa, CRANIO and Neuromate-based robotic systems, the time of craniotomy (about 7 min) was only measured in RobaCKa robot, however the other two researches had only performed uncontrolled trial of 5 cases respectively to test the robots on plastic foam skull models. So their results cannot demonstrate a superiority of craniotomy robots scientifically [8–11]. University of Chang Gung in Taiwan had developed the navigation-guided robotic arm drilling system [14], University of Utah in USA had developed the computer-aided design surgical drilling system, both of them only calculated the average distance errors between the planned path and the risk area(0.502 mm and 1 mm). Time spent of craniotomy was measured as about 2 min and 30 s in the latter research [28]. The study Aung2021 developed a man-machine interactive robot to perform craniotomy, but it only perform 5 model experiments [12]. These three studies had only performed uncontrolled trials of small sample sizes too. Overall, previous robot systems lacked safety, because they all automatically performed craniotomy according to the preoperative planned path without the intervention of surgeons. Their superiority, safety and efficiency were uncertain, because among these researches no controlled trials were performed on subjects of large sample sizes simulating actual skull. Another study Xu2021 used similar method of human-machine collaborative control to design the robot-assisted craniotomy system. Their animal experiment showed similar

**Table 1**
Comparison experimental results of position error, time spent and injury incidence.

| Variable | Skull model | | | Mini pig | | |
|---|---|---|---|---|---|---|
| | Experimental group (n = 16) | Control group (n = 16) | P | Experimental group (n = 10) | Control group (n = 10) | P |
| Position error (mm, $\overline{x}$± *sd*) | 1.87 ± 0.66 | 3.14 ± 0.73 | **<0.001** | 3.26 ± 0.51 | 4.39 ± 0.75 | **0.008** |
| Total time spent (min, $\overline{t}$± *sd*) | 6.64 ± 1.15 | 8.06 ± 1.10 | **0.001** | 11.83 ± 0.92 | 26.10 ± 1.62 | **<0.001** |
| Robot setting up and navigation process | 3.44 ± 0.98 | 3.75 ± 1.00 | 0.39 | 6.42 ± 0.65 | 7.10 ± 1.12 | 0.11 |
| Craniotomy surgery | 3.20 ± 1.02 | 4.32 ± 0.64 | **0.001** | 5.41 ± 0.66 | 19.00 ± 1.54 | **<0.001** |
| Injury incidence (%) | 6.3 | 18.8 | | 0 | 20.0 | |

accuracy with our Cranibot (2.02 versus 3.26 mm). But their robot system took more time than our Cranibot in craniotomy surgery process (including drilling and milling) (10.97 versus 5.41 min). Its incidence of complications was also higher than our study (12.5 % versus 0 %). Its sample size was smaller than our study and it did not perform experiment on skull model [13]. In addition, the navigation system algorithm was designed for sphere. The structure of pig's head was not a sphere and more complex than the skull model so that its navigation process took more time.

This study designed an intelligent human-machined collaborative control robot-assisted craniotomy system, which achieved human-machine interaction through force sensor at the end of the robotic arm and achieved robot-environment interaction through real-time adjustment of craniotomy track by information of force feedback of environment. It not only exerted the efficiency and stability of robot, but also ensured safety through the motion control of robotic arm by giving multi-sense feedback to surgeons. A controlled trial was also carried out on the robot to test its accuracy, efficiency and safety.

The results of this study showed a good motion fluency of the robotic arm. In terms of force feedback, compared with hands of surgeon, the six-DoF force sensor on the end of robotic arm can provide a more accurate and sensitive force feedback. The feed forces of the two experimental subjects were different, which would be caused by different hardness and thickness of models and pig's head. The sudden changes of torque were the signal of drilling through the skull, which was passed to robot controller to shield the feed force of surgeon and robotic arm resulting in the motion of robotic arm only in the opposite direction and the safety assurance of drilling. The contact force during milling was about $\pm 2$N in the experiments of models and animals, which fully demonstrated the stability of the robot during milling.

Accuracy: The results of experiment showed that the position error of "robot" group was smaller than that of "surgeon" group and the difference was statistically significant, which fully indicated the advantage of the Cranibot in accuracy. During drilling and milling, the position error of mini pigs experiment was more than that of skull model experiment due to the flattened shape of the pig's skull which caused less characteristic data obtained by registration. The self-designed registration program registered the preoperative CT data with the intraoperative data obtained by scanning the skull using the positioning probe. Through the spatial registration of four coordinate systems (the coordinate systems of skull, optical navigation system, robot and 3D reconstructed image), the robotic arm was controlled and guided to move from start point to target point according to preoperative plan [29,30]. The navigation registration algorithm was planned in the future to be optimized to improve the positioning accuracy within 1 mm.

Efficiency: The Cranibot system performed craniotomy much faster than surgeons, which achieved a main goal of this research. The time spent on craniotomy in model experiment was less than that in mini pig experiment ($6.64 \pm 1.15$min VS $11.83 \pm 0.92$min), which may be caused by the more thick and unique structure (a wide cavity existed between a double-layer structure of skull) of pig's skull. The robotic arm was found that can only drill into the skull vertically according to preoperative plan without the ability of angle adjustment in case that the drill had great resistance or can't continue to move ahead. So we considered to design a program that enable the robotic arm tilt and rotate appropriately around the drilling point, at same time, design a on and off switch to achieve the convenient cutover of "robot" mode and "surgeon" mode.

Safety: The total incidence of tissue injury in the experimental group and the control group of the two different subjects were 3.8 % (1/26) and 19.2 % (5/26), which were all significantly lower than the incidence of dura tear of manual craniotomy (30 %) reported in the previous literature [31]. Tissue injury were mainly dura tear and vascular damage. And there was no significant difference in the incidence of tissue injury between the experimental and control groups, which may result from the insufficient sample sizes. Further research of large sample sizes was needed and much more animal experiments and cadaveric head experiments should be performed to obtain more data support of the robot's efficacy before clinical trials.

Although we chose mini pigs with similar weight and volume of head to perform experiment, the anatomical differences of their skull cannot be avoided, which may cause bias of results. Anatomical differences of human skull actually exist generally, so this bias can be accepted. Other confounding factors included the experience of surgeon and craniotomy tool. To control the bias, all the craniotomy was performed by one surgeon and by the same drill and mill. Although robot-assisted surgery is still insufficient compared with traditional surgery, we thought that the attempt of robot-assisted craniotomy research is necessary. Because of the limited volume of skull cavity (no like the enough volume and expansionary of chest and abdominal cavity), the complex craniotomy, such as skull base surgery, cannot be completed by robot. However our results of experiment showed that supratentorial craniotomy can be performed by our robot-assisted craniotomy system. Further research should be performed to prove its applicability in neurosurgery in future.

## 5. Conclusion

This intelligent human-machine collaborative robot-assisted system can perform craniotomy fluently and successfully and improve the accuracy and efficiency of craniotomy, in addition provide precise force feedback to surgeons. Although the safety of Cranibot in avoiding tissue injury was not detected as superior to that of manual craniotomy according to statistical analysis. However the injury incidence of robot-assisted craniotomy was already lower than manual craniotomy from the data perspective. So we are confident that the safety of Cranibot can be further confirmed by cadaveric head experiment and vivo experiment of large samples. Along with the improvement of robot system and experiments of large sample sizes, more accurate results will be acquired and sensitivity of force feedback and flexibility of robotic arm will be enhanced.

## CRediT authorship contribution statement

**Meng Cui:** Writing – review & editing, Writing – original draft, Visualization, Validation, Investigation, Formal analysis, Data curation, Conceptualization. **Wenqing Ren:** Writing – review & editing, Methodology, Data curation. **Tengfei Cui:** Writing – review & editing, Software, Resources, Methodology, Data curation. **Ruifeng Chen:** Writing – review & editing, Supervision, Resources, Data curation. **Yi Shan:** Writing – review & editing, Supervision, Resources, Methodology. **Xiaodong Ma:** Writing – review & editing, Supervision, Project administration, Methodology, Formal analysis, Conceptualization.

## Ethics statement

The animal experiment was authorized by the Animal Experiment Welfare and Ethics Committee of Chinese PLA General Hospital. The ethics approval number was 2017-D12-55.

## Data and code availability statement

Data will be made available on request.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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