

Evaluation of a Custom-designed Control System of Human-Robot Collaboration for Dental Implant Placement.

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Abstract Abstract Background: The purpose of this study is to develop a methodology to better control a human–robot collaboration for robotic dental implant placement. We have designed a human–robot collaborative implant system (HRCDIS) which is based on a zero-force hand-guiding concept and a operational task management workflow that can achieve highly accurate and stable osteotomy drilling based on a surgeon's decision and robotic arm movements during implant surgery. Method: The HRCDIS brings forth the robot arm positions, exact drilling location, direction and performs automatic drilling. The HRCDIS can also avoid complex programing in the robot. The purpose of the study is to evaluate the accuracy of drilling resulting from our developed operational task management method (OTMM). The OTMM can enable the robot to switch, pause, and resume drilling tasks. The force required for hand-guiding in a zero-force control mode of the robot was detected by a 6D force sensor. We compared our force data to those provided by the manufacturer's manual. The study was conducted on a phantom head with a 3D-printed jaw bone to verify the validity of our HRCDIS. We appraised the discrepancies between free-hand drillings and the HRCDIS controlled drillings at apical center and head center of the implant and implant angulation to the baseline data from a virtual surgical planning model. Results: The average required force used by hand-guiding to operate the robot with HRCDIS was near 7 Newton which is much less than the manufacturer's specification (30 Newton). The results from our study showed that the average error at implant head was 1.04 ± 0.37 mm, 1.56 ± 0.52 mm at the implant apex, and deviation of implant angle was $3.74 \pm 0.67^\circ$. Conclusions: The results from this study validate the merit of the human–robot collaboration control by the HRCDIS. Based on the improved navigation system using HRCDIS, a robotic implant placement can provide seamless drilling with ease, efficiency and accuracy

Introduction Different types of dental implant robots developed are an autonomous drilling system that generates a motion trajectory based on the preoperative virtual planning during its autonomous drilling process. Factors may cause drilling errors including discrepancies between actual bone and measured data on CBCT images, temporary adjustment of implant sites and intraoperative bleeding. Robot drilling is more stable and accurate than free-hand drilling for implant placement. Good human–machine coordination among a robot, an operator, and a patient is important during implant surgery. Our human–robot collaborative implant system (HRCDIS) consists of a zero-force hand-guiding scheme and an operational task management system for the human–machine collaborative process and control maneuver. In this study, we tested and validated the accuracy of our HRCDIS.

Materials and Methods We have developed our HRCDIS using a visual position tracking system (optical camera and positioning marker) and a modified UR5 Cobot (the Universal Robots company, Odense, Denmark). Detailed information of the HRCDIS could be found in our previous work. The human–robot collaborative interaction block diagram of HRCDIS is shown in Figure 1. It includes zero-force control, virtual implant planning, visual positioning, and terminal control of the robot. The robot recognizes the operator's intention through a zero-force control mode and controls an end-effector device to follow a manual movement. The conversion from the implanting coordinate system to the patient coordinate system can be obtained by using positioning markers, as shown in Figure 6A. A fixed guide marker is designed based on the patient teeth surface in a 3D implanting plan.¹⁷ A guide marker can effectively fit a patient's teeth and synchronize the movement of the fixed guide plate with the patient's dental implant hole so that the TO P becomes a constant matrix. The conversion from the implanting coordinate system to the patient coordinate system can be obtained by using positioning markers. For verifying the effectiveness of human–robot collaboration control for dental implanting operation procedure with the HRCDIS, a self-made experimental model was designed to conduct drilling experiments, which could use to simulate the implant drilling. The preoperative plan was to implant five implants in the positions of tooth #35, #36, #45, #46, and #47. The experiment scene, implant plan, and Equipment. To evaluate the effect of zero-force control, a 6D force sensor HEX-E QC (Onrobot Inc.) is used to measure the force of hand-guiding with or without zero-force control of UR5. After mounting the sensor on the robot. The robot was dragged to the manufacturer-provided teach mode and zero-force control mode, respectively. The forces required to move the robot arm from static to motion in these two modes were recorded.. The operation process and detailed description of HRCDIS and the experiment are shown in Figure 11. The robot is autonomously positioned finely according to the position provided by Equation 5 after hand-guided to a proper position. Where the undefined vectors n and o are determined by the robot's current poses. After the auto- positioning, the pose of robot can be manually adjusted along the axial direction of the dental drill, according to the actual situation, in order to avoid potential interference.

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graph LR
    User[User] -- "ED-Frank sensor data" --> Gravity[Gravity compensation]
    Gravity --> Zero[Zero force Control]
    Robot[Robot] -- "visual detecting" --> Position[Position of marker]
    Robot -- "implant plan" --> Coord[Coordinate conversion]
    Position --> Planning[Robotic planning action generation]
    Coord --> Planning
    TaskMgmt[Task Management] --> Planning
    Planning -- "Robotic planning action command" --> Tasks[Hand-guiding task<br/>Automatic robot positioning tasks<br/>Robot cavity preparation task]
    Planning -- "Starting position" --> Tasks
    Tasks --> TaskMgmt
    Zero --> TaskMgmt
    TaskMgmt --> Robot
  
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The diagram illustrates a control system for a robot. It consists of the following components and signal flows:

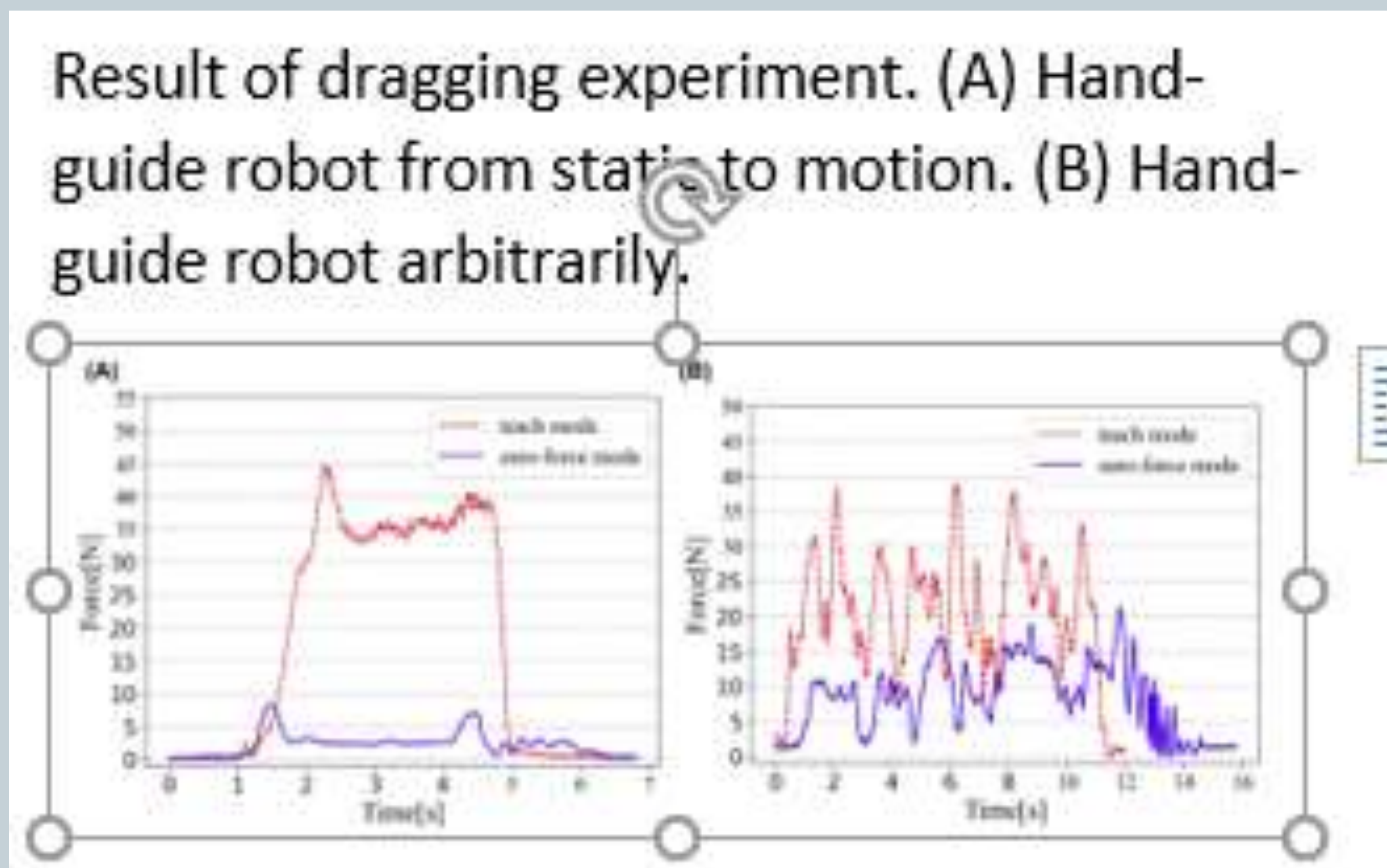
- Zero-Force Balance**: Receives an external force F_{ext} and outputs acceleration q'' to the **Robot positive dynamics** block.
- Robot positive dynamics**: Receives q'' and outputs desired displacement $q'd$ to the **Robot control box**.
- Robot control box**: Receives $q'd$ and outputs the actual displacement q to the **Gravity compensation** block and a derivative block s .
- Gravity compensation**: Receives q and outputs a compensation force M, g to the **Zero-Force Balance** block.
- Derivative block (s)**: Receives q and outputs velocity q' to the **Robot positive dynamics** block.

The diagram illustrates the task migration process across three stages:

- Task Pool:** Contains a list of tasks, each with a 'Serial number' and segments (Segment 1, Segment 2, Segment 3, ..., Segment n). A 'Task ID' is associated with each task.
- Sync area:** A task is selected from the Task Pool and its segments are copied to the Sync area. The 'RTDE' (Real-time Data Exchange) is used for this process. The task is then scheduled, and its segments are copied to the Staging area.
- Staging area:** The task is executed, and its segments are copied back to the Task Pool. The 'Override get frequency' is used for this process.

Experimental Results

Comparison of typical forces required to move the dental robot arm from static to motion by a dragging experiment with our zero-force mode and manufacture's mode. To drag the robot from rest to motion, it only takes 3–4 N with the HRCDIS integrated system. Conversely, it takes 30–40 N to complete the same action following the manufacture's recommendation. The required forces are significantly reduced with the HRCDIS system (1/10th of the forces needed).



Test method of the accuracy of hole preparation. (A) The implanted mimic model, and (B) the 3D model which scanned from (A), and (C) the registration and error of the preoperative and postoperative models, (D) a comparison of planned and actual planting locations, (E) the implant accuracy evaluation index, and (F) one of the actual measurement results.

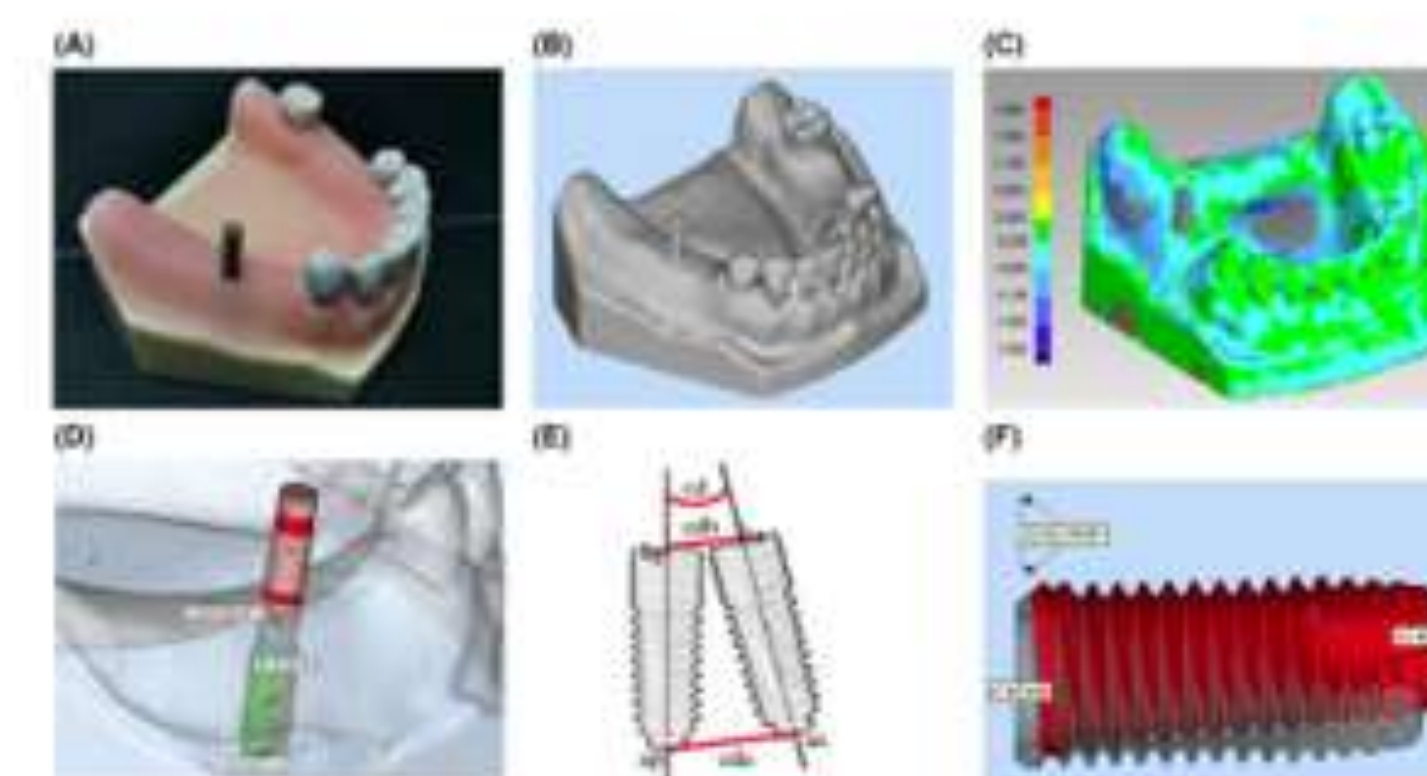


TABLE 1 The deviations of distance and angle

Tooth position (-times)	<i>cdh</i> (mm)	<i>cda</i> (mm)	<i>ad</i> (°)
35-1	0.95	2.52	3.64
36-1	0.52	1.01	4.09
37-1	1.38	0.54	4.96
45-1	1.52	2.40	3.20
46-1	1.62	1.82	4.10
35-2	1.14	1.59	4.44
36-2	1.14	1.45	4.39
37-2	0.73	0.90	3.46
45-2	0.82	1.74	2.58
46-2	0.94	1.52	4.21
35-3	0.51	1.32	3.33
36-3	0.88	1.84	2.86
37-3	1.20	1.93	2.95
45-3	0.64	1.50	3.81
46-3	1.60	1.38	4.05
Min	0.51	0.54	2.58
Max	1.62	2.52	4.96
Means	1.04	1.56	3.74
Std	0.37	0.52	0.67

- **Conclusions**

We have developed a human–robot collaborative implant operation mode with a zero-force hand guiding system, autonomous robot positioning, posing, and drilling, as well as an operational task management system. We evaluated the accuracy of the HRCDIS for implant drilling and the force required for the zero-force hand-guide. Our human–robot collaboration mode confirmed that the HRCDIS meets the clinical requirements in terms of implant drilling accuracy and the system offers a user-friendly model for robotic dental implant surgery. In the future, we will further promote the hand-guiding operation experience of HRCDIS, analyze dental implant-related surgery, and design further user operations to enhance human–robot collaboration experience.