ROBOT-ASSISTED SYSTEM FOR JOINT FRACTURE SURGERY

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INTRODUCTION

Incidence of fractures is steadily increasing and is expected that in 2025, Germany will have the largest number of fractures per year in Europe (≈928,000), followed by the UK (≈682,000) (Hernlund 2013). This work is concerned with distal-femur-fractures (DFF) where the bone breaks either straight across or into many pieces, extending into the knee joint and separate the articular surface of the bone into fragments. Because they damage the cartilage surface of the bone, intra-articular fractures can be difficult to treat. When the distal femur breaks, hamstrings and quadriceps muscles tend to contract and shorten the fracture, changing fragment position and making line up with a cast difficult to achieve (Kulkarni 2008). The traditional treatment of DFF is surgical manual reduction and rigid internal fixation of these fractures using metallic plates and screws (Muller 1991) involving open incisions into the knee. Manipulating diminutive fragments to a high-standard of positional accuracy is critical to avoid clinical complications and to ensure a complete recovery from the injury (Gaston 2005). At the same time, a minimally invasive approach is crucial to minimise surgical impact on soft tissues and reduce the recovery time. We believe that robotic assistance can have a positive impact in this field, allowing more accurate fracture fragment repositioning without open surgery, and obviating problems related to the current manual percutaneous surgical techniques. Robot-assisted fracture surgery (RAFS) is potentially able to combine the required high-positioning accuracy with the minimally invasive approach, reducing in-patient stays and making recovery swifter and more complete.

MATERIALS AND METHODS

Our research toward improving joint fracture surgery has resulted in the creation of the robot-assisted system for the reduction of intra-articular joint fractures here presented (Fig.1). This system will allow the surgeon to reposition a bone fragment attached to the robot (a pin connects the robot and the fragment through a small incision) with submillimetric accuracy.

The system consists of a 6-DOF parallel-robot (Fig.1a) controlled in real-time from a computer workstation. The six parallel-robot struts were designed as linear actuators arranged in a Universal-Prismatic-Spherical hexapod configuration (Mruthyunjaya 1998). The actuation element is a brushed DC motor with integrated gearbox and rotational encoder (MAXON®). The control workstation employs a host-target structure (Fig.1b) composed by a host-computer, a real-time controller, and a field-programmable-gate-array (FPGA). The host-computer runs a graphical-user-interface (GUI) to configure and monitor the robot, communicating via ethernet with the real-time controller, which is responsible for the high-level control of the system. The real-time controller connects with the FPGA (via Direct-Memory-Access), which interfaces with the low-level motor controllers (EPOS2-MAXON®) using the CAN-bus protocol. The software for the control workstation is written in LabView (National Instruments).

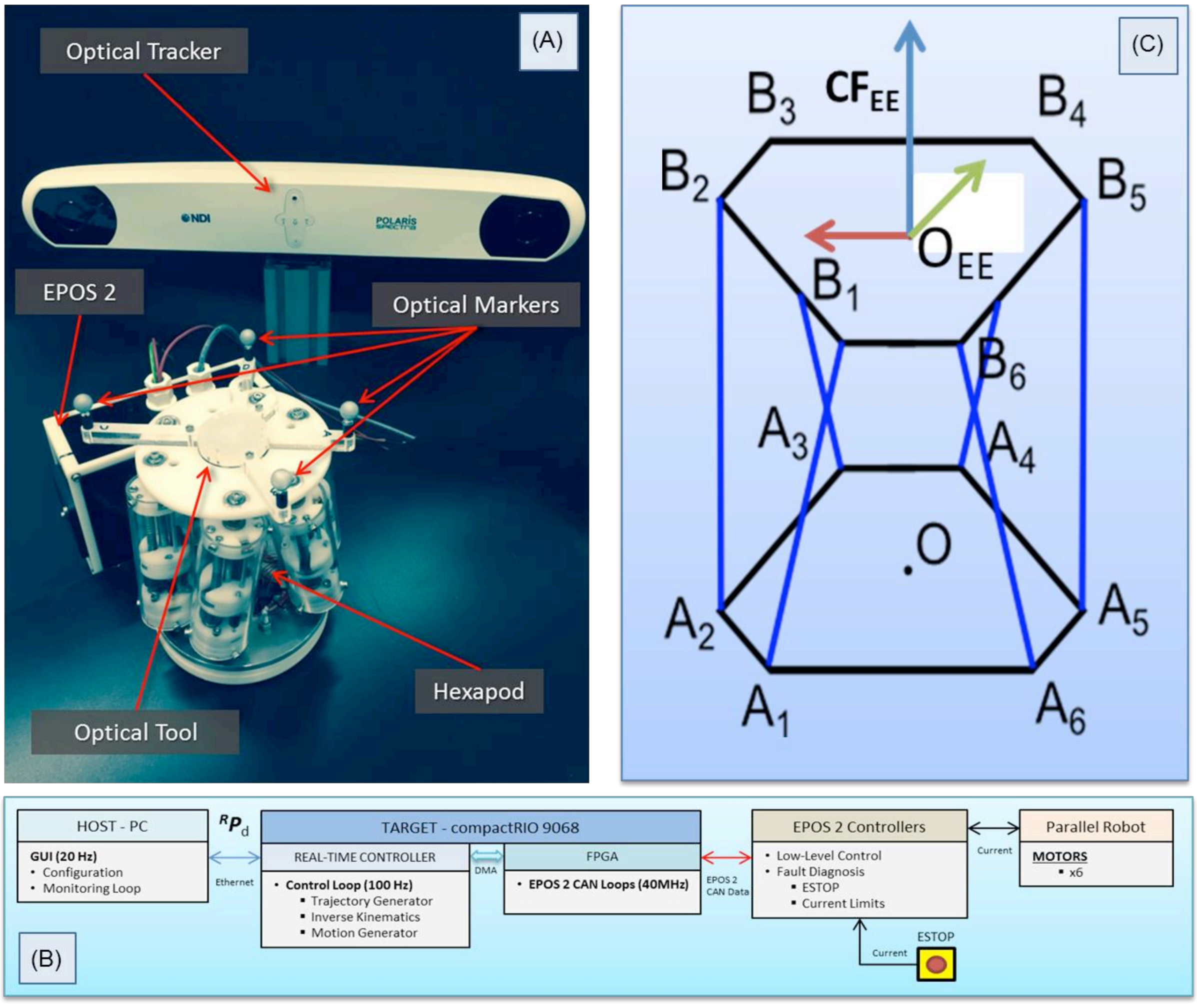

Figure 1: The parallel-robot and the EPOS2 controller, together with the optical tracker and tools used in the experiment (A); Control workstation architecture (B); and the parallel-robot kinematic chain representation (C).

An open-loop controller uses individual motor encoders to control the robot's pose in the task space. This is based on the parallel-robot inverse kinematics and the relevant schematic is shown in (Fig.1b): the surgeon defines a desired pose for the robot end-effector RPd through the GUI, the trajectory generator generates a trajectory for the robot to reach the desired pose, while the inverse kinematics calculates the motion commands for the six robot struts. The inverse kinematics is derived using the loop closure approach for each strut (Fig.1c):

$$\left\| A_i B_i \right\| = \sqrt{(x_{B_i} - x_{A_i})^2 + (y_{B_i} - y_{A_i})^2 + (z_{B_i} - z_{A_i})^2} \qquad i=1\ldots6 \qquad (1)$$

The length values from (1) are the commands delivered to the motion generator system that synchronises the six actuators using a velocity feed-forward control scheme (Raabe 2012). These motion data are sent to the FPGA that generates motion CAN commands and sends them to the EPOS2 controller, which provides a low-level control for the linear actuators in order to reach the desired pose.

A set of 18 positioning trials was conducted aiming at characterising the system through quantitative measurements of its positioning accuracy. Each trial included moving the robot end-effector along x, y, z axes (translations), and rotating it around the three axes (roll, pitch, yaw) from a start to end position with incremental steps of 0.2mm, 0.5mm, 1mm (translation), and 0.2°, 0.5°, 1° (rotation). Start and end positions were chosen in order to cover both negative and positive directions. The overall number of targets for the experimental set was 378. All positioning manoeuvres were executed individually along and around a single axis per trial. An optical tracker (Polaris Spectra-NDI Inc.) provided the actual pose of the robot end-effector by tracking the optical markers placed on the robot according to a known geometry (Fig.1a). The optical tracker acquired the actual position of the robot end-effector at each target point, allowing the measurement of positional accuracy as position errors, i.e. the root-mean-squared-error (RMSE).

RESULTS

The experimental results from the positioning trials are summarised in Table1.

Axis of Motion	x	y	z	Roll	Pitch	Yaw
	mm			degrees		
RMSE	*0.51 ± 0.27*	*0.48 ± 0.21*	*0.05 ± 0.01*	*0.07 ± 0.01*	*0.06 ± 0.01*	*0.29 ± 0.07*
Number of Targets	*63*	*63*	*63*	*63*	*63*	*63*

Table 1: Results from positioning trials.

DISCUSSION

Joint fracture surgery imposes challenging accuracy requirements, i.e. translational and rotational alignment accuracy for optimal clinical outcome shall be <1mm and <5° respectively (Raabe 2012). Manipulating joint-related bone fragments to a high positional accuracy is a complex problem, and it is different from already established robot-assisted surgery in orthopaedics focusing on automated milling of rigid bone surfaces such as Robodoc (Paul 1992), Acrobot (Jakopec 2001), or the systems proposed by Tang (Tang 2012) and Westphal (Westphal 2009). We propose a system to meet these requirements.

The positioning experiments demonstrated that the system is precise, achieving submillimetric translation errors (about 0.5mm along x-y axes, 50μm along z), and rotation errors of less than 0.3° (0.065° around roll-pitch axes, 0.3° around yaw). The level of accuracy emerged in the experimental trials is highly reliable for fracture surgery applications, leading to the conclusion that the proposed system meets the requirements (<1mm, <5°).

In the next steps, the visual-feedback provided by the optical tracker will be used to close the position control loop, improving the overall system accuracy and reliability. Also, the optical tracker will be used for the real-time co-registration and tracking of the fragments. Finally, a force/torque sensor will be integrated into the system to enable hybrid force-position control to deal with the constraints related with the soft tissues.

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