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Paper title: Vision-Based Real-Time Position Control of a Semi-automated System for Robot-Assisted Joint Fracture Surgery

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Abstract:
Purpose: Joint fracture surgery quality can be improved by robotic system with high accuracy and repeatability fracture fragment manipulation. A new real-time vision-based system for fragment manipulation during robot-assisted fracture surgery was developed and tested.

Methods: The control strategy was accomplished by merging fast open-loop control with vision-based control. This two-phase process is designed to eliminate the open-loop positioning errors by closing the control loop using visual-feedback provided by an optical tracking system. Evaluation of the control system accuracy was performed using robot *positioning trials*, and fracture reduction accuracy was tested in trials on ex-vivo porcine model.

Results: The system resulted in high fracture reduction reliability with a reduction accuracy of 0.09mm (translations) and of 0.15° (rotations), maximum observed errors in the order of 0.12mm (translations) and of 0.18° (rotations), and a reduction repeatability of 0.02mm and 0.03°.

Conclusions: The proposed vision-based system was shown to be effective and suitable for real joint fracture surgical procedures, contributing a potential improvement of their quality.

Conflict of Interest Statement
Giulio Dagnino, Ioannis Georgilas, Payam Tarassoli, Roger Atkins, and Sanja Dogramadzi declare that they have no conflict of interest.

Approval by Ethics Committee
An approval by an ethics committee was not applicable.

Informed Consent
Statement of informed consent was not applicable since the manuscript does not contain any patient data.

Text

Introduction

Fractures cause substantial costs and considerable disability [1]. The incidence of fractures is steadily increasing in ageing societies and is expected that in 2025, Germany will have the largest number of fractures in Europe with approximately 928,000 fractures, followed by the UK with approximately 682,000 fractures per year [2]. Most of the fractures are caused by ageing and osteoporosis [2]. Portions of these are intra-articular fractures where the break crosses into the surface of a joint and are, typically, more difficult to manage. These fractures in younger patients are usually caused by high energy impacts, such as falls from significant heights or motor vehicle collisions. Elderly people typically have poor bone quality (i.e. osteoporosis). A lower-force event, such as a fall from standing, can cause a distal femur fracture in an older person who has weak bones [3]. Intra-articular fractures are treated either with open surgery that requires massive soft tissue incisions or using minimally invasive surgery (MIS) with small incisions that when performed by surgeons and supported by x-rays do not always achieve the required accuracy of surgical treatment [4] but allow more rapid patient recovery time and lower complication rate [5]. This work is concerned with distal femur fractures (DFF) where the bone breaks either straight across (transverse fracture) or into many pieces (comminuted fracture), extending into the knee joint and separate the articular surface of the bone into a few (or many) parts. Because they damage the cartilage surface of the bone, intra-articular fractures can be more difficult to treat. When the distal femur breaks, the muscles around the thigh (hamstrings and quadriceps) tend to contract and shorten the fracture, changing bone fragment position and making line up with a cast difficult to achieve [3]. Currently, the traditional treatment of DFF is anatomical surgical reduction and rigid internal fixation of these fractures [6] involving an open incision into the knee, manual reduction of the fracture, and fixation using a combination of metallic plates and screws. In joint fracture surgery, 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 [7]. At the same time, a minimally invasive approach is crucial to minimise surgical impact on soft tissues and reduce the recovery time. These requirements, together with the issues identified above, lead us to 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, hugely reducing in-patient stays and making recovery swifter and more complete.

Robot assistance in the operating theatre has been increasing since the 1980s [8] and is currently helping surgeons with new procedures and achieving unprecedented levels of performance [9]. Major technological goals are to improve the surgical outcome, reduce operating time, and improve patient safety. Manipulating joint-related bone fragments to a high positional accuracy is a complex problem, and it is different from already established robotic assisted surgery in orthopaedics focusing on automated milling of rigid bone surfaces such as the robot offered by MAKO corporation [10]. Robot-assisted fracture reduction has already been attempted for long bone

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reduction [12–15], specifically femur shaft fractures. Westphal *et al.* [11] proposed a robotic system for the reduction of femur shaft fractures based on a telemanipulated industrial serial robot. The surgeon control the telemanipulated system from a console equipped with a joystick with force feedback to manipulate bone fragment attached to the robotic system. An optical navigation system is used to track the pose of the bone fragments. However, the visual feedback provided by the optical tracker is used to close the control loop through the surgeon. Therefore the control variables depend on the judgment of the human operator and the manipulation is prone to positional errors. Warisawa *et al.* [12] described a fracture reduction robot, which follows the principle of orthopaedic traction tables (i.e. an operating table, which allows the application of a constant and adjustable pull). Mounted to the patient's foot, this robot performs, and respectively supports, the reduction procedure of the femur via the knee joint. 6-axis force sensor is installed on the backside of the fixture boot to realize power assist capability to enhance operability. The force sensor provides a capability to measure the force applying on the patient's femur as well. A commendable aspect of their robot assistance concept is, however, its non-invasiveness that certainly is a big advantage. However, this concept limits the usability of the robot as it seems to be difficult or impossible to utilize it for other fracture types. Wang *et al.* work [13] focused again on femoral shaft fracture reduction using a parallel manipulator robot mounted on a traction table to achieve a better alignment of the fractured femur. One end of the manipulator is attached to the distal portion of the fractured femur while the proximal end is fixed to the operating bed. The manipulator provides both traction and rotation to align the fragments and reduce the fracture. Similarly, Tang *et al.* [14] reported on the design and test of a hexapod computer-assisted system for the reduction of diaphyseal femur fractures. The hexapod is composed of two identical rings connected by six actuated struts, like a Taylor Spatial Frame [15]. Fracture fragments are attached to the proximal and distal rings, and the robot based on software commands reduces the fracture. However, both papers do not describe control schemes as well as the load capacity of the manipulator. These systems don't implement neither closed-loop position control nor integrate a load cell sensor for force/torque feedback, both essential for reliable and safe clinical applications. Also, the described systems are restricted to long bone fractures, attempting to solve a different problem.

However, compared with fractures that involve joints, femur shaft fractures have smaller number of larger fragments that present a 2D problem for surgical reduction and are perceived easier to manage in the clinical setting. Intra-articular fractures are 3D fractures and are, therefore, more difficult to solve using 2D intra-operational images. Also, femur shaft fractures require a lower level of manipulation accuracy to be reduced.

At the Bristol Robotics Laboratory (BRL), research toward improving joint fracture surgery has resulted in the creation of the robot-assisted system presented in this paper and shown in Fig.1. This is a semi-automatic positioning system for the reduction of intra-articular joint fracture based on a 6-DOF parallel-robot mounted on a carrier platform, controlled in real-time from a computer workstation. This system will allow the surgeon to reposition a bone fragment attached to the robot with submillimetric level of accuracy and repeatability through a robust vision-based control system. The connection between the robot and the fragment is obtained through a metallic orthopaedic pin. The reduction process consists in the following procedure: 1) the surgeon drills the fragment that has to be manipulated; 2) screws the pin in the fragment; 3) connects the pin to the moving plate of the robot; 4) manipulates the fragment using the proposed system; 5) checks the reduction accuracy through

fluoroscopic images. This solution was inspired by the preliminary work on RAFS conducted at the BRL [16–18], and by the concept of visual feedback [19, 20].

In summary, the objective of this study is to design and control a robotic system to meet the challenging accuracy and repeatability requirements for fragment manipulation in minimally invasive joint fracture surgery. The paper also reports on the positioning and repeatability experiments conducted in the laboratory, in order to demonstrate that the proposed system is able to fulfil these demanding clinical requirements.

System Configuration

The system for robot-assisted fracture surgery (RAFS system) proposed in this research (Fig.1) consists of a parallel-robot, a carrier platform, a tracking system, and a control workstation for processing the data and controlling the robot. The RAFS system is also provided with a force-torque sensor (6-DOF force-torque load cell - FTSens, Istituto Italiano di Tecnologia, Italy) whose feedback data are used as a safety feature for the system: if the measured force-torque data exceed predefined thresholds, then the force controller immediately stops the movement of the robot to avoid damages to the patient.

Specifications for dimensioning the surgical system were established through discussions with orthopaedic surgeons and analysis of various fracture cases [16, 21–23]. Because the fracture includes the knee joint, small misalignments may have adverse long-term effects on the joint mechanism [23]. Fractures that affect the knee joint, e.g. distal femur fractures and tibial plateau fractures, with fragment dislocations bigger than 5° and 1mm should be treated surgically [22, 23]. Also, high impact fractures can cause dislocations of more than 2 cm and 60-180° [22, 23]. During surgical reduction the fracture fragments should be accessed avoiding the surrounding blood vessels, nerves and muscle/ligament tissue. The approach is typically made through the anterior (front) of the limb ±120$^{\text{o}}$ from its vertical axis (Fig.2a) or from the lateral or medial side ±60$^{\text{o}}$ around the side axes of the limb. (Fig.2b) The combined 'approach' envelope is a spherical section (Fig.2c). Based on this geometrical requirement, an optimal robot workspace should have a hollow hemisphere shape (Fig.2d).

The required load capacity for the system has been defined by in vivo measured forces applied by surgeons during lower limb surgical procedures. We instrumented a periosteal elevator and a traction table with two 6-DOF load cells, developed a dedicated data acquisition software, and analysed the force/torque data as reported in [24, 25].

A summary of the parameters that informed the system design is reported in Table 1.

Robot structure

A parallel-robot for fracture fragments manipulation has been mounted on a carrier system in order to cover the required surgical workspace (Fig.2). Compared with industrial serial robots, parallel-robots are significantly stiffer, have greater load capacity, cost less, and are more compact in size [26]. Therefore, the use of a parallel-robot

is a preferred choice for the fine movements required in fracture surgeries [13, 14, 27], where high load carrying capacity and precise positioning accuracy-repeatability are of paramount importance.

High precision commercial parallel-robots are expensive especially when purpose built. The parallel-robot for fracture reduction has, therefore, been designed and manufactured in-house [18] with the following characteristics. The struts have been developed as linear actuators based on a layered design consisting of laser-cut acetal sheets varying in thickness from 1-5mm. The linear guide elements (ball screws, linear shafts) are made of ground hardened steel allowing for high precision tolerances. The actuation element is a brushed DC motor with integrated gearbox and rotational encoder (MAXON® RE10 – MR – GP10K) providing high-torque, precise positioning while allowing for a simple assembly solution. The minimum displacement for each linear actuator is 0.485μm. The struts are arranged in a Universal-Prismatic-Spherical (UPS) hexapod configuration [28]. The parallel-robot is shown in Fig.1a. Six motor controllers (MAXON® EPOS2™ 24/3) are responsible for the low-level implementation of positional, velocity and current control based on the required motion profiles generated by the high-level control. The communication protocol is CANopen with the command set provided by the manufacturer (MAXON®).

Compared to other parallel-robots in the literature utilised for medical applications [11–14, 27, 29], the novelty of the proposed system is its manufacturing procedure. Although the hexapod has been produced with a non-typical methodology (i.e. not permanently assembled (glued) layered parts) for precision mechanism, it still retains the excellent performance characteristics of commercially available and custom built systems (i.e. precision, rigidity, load capabilities). At the same time this provides an easy-to-repair approach that with minimal alterations, namely the addition of external metal casing, can be utilised as such to closer-to-clinical testing conditions.

Each strut can produce a maximum force of 152N based on the given motor and actuation system, (ball screw) calculated using (1):

$$F = \frac{2 \times \pi \times r \times T}{p} \tag{1}$$

where F is a linear force exerted by the ball screw nut, r is the efficiency of the ball screw (typically 0.9), T is the input torque to the ball screw (in this case the torque is 0.096Nm), and p is the pitch of the ball screw, 2mm. The actual maximum force applied by a single strut is limited to 60N to prevent a possible structural failure. This is a safety feature of the system. As a result of this the robot is able to generate an overall maximum load capacity of 360N (force) and 12 Nm (torque), calculated using [30], and satisfying the requirements for fragment manipulation reported in Table 1.

Given the fabrication technology and the tolerances of the actuation system, the parallel-robot has repeatability of 0.058mm per strut. The overall hexapod precision, calculated using [31], is 0.137mm.

The parallel-robot has translational limits of ±10.25mm along x, y, ±15mm along z and rotational limits of ±17° around each axis. In order to fully cover the surgical field, it is mounted on a UR10 (Universal Robots A/S,

Denmark) robotic carrier platform (CP). The UR10 is a 6-DOFs serial manipulator with active compliant behaviour that has been certified for use in a close proximity of human operators. This specific model (UR10) has a payload of 10Kg with a repeatability of 0.1mm. UR10 can lock its joints by engaging mechanical brakes. This can maintain a position without the need for continuous active control. This feature is utilised for a coarse positioning of the parallel-robot close to a desired position where the parallel-robot performs final (fine) fracture reduction. Since the UR10 has a spherical workspace of 1300 mm in radius, the proposed hybrid robotic system (CP + parallel-robot) covers the required surgical workspace, as illustrated in Fig.3.

Design parameters for the robot are summarised in Table 2.

Optical tracking

Optical tracking is used to measure the actual pose of the robot end-effector coordinate frame located in the centre of the moving plate O_{EE} (see Fig.6a). The system uses a Polaris Spectra (NDI Inc., Waterloo, Ontario, Canada), an optical infrared laser measurement device (Fig.1a). Using optical markers placed according to a known geometry (i.e. optical tool in Fig.1a), the position and orientation of the associated coordinate frame can be measured. According to the manufacturer, the position of an optical tool in the tracking area can be determined with a remaining root mean squared (RMS) error of less than 0.3mm. The data derived from the tracker contain the translation $^{C}\boldsymbol{T}_a = (^{C}x_a, {}^{C}y_a, {}^{C}z_a)$ and the orientation represented in unit quaternion format $^{C}\boldsymbol{Q}_a = (^{C}q0_a, {}^{C}qx_a, {}^{C}qy_a, {}^{C}qz_a)$. An optical tool has been designed and manufactured in-house, to be rigidly attached to the end-effector; its pose is measured in the optical tracking system reference frame CF_C and processed to get the transformation matrix $^{C}\boldsymbol{T}_{T,EE}$ between the optical tracker and the optical tool mounted on the hexapod moving plate. The optical tool coordinate frame $CF_{T,EE}$ is coincident with the coordinate frame of the end-effector CF_{EE}: $CF_{T,EE} = CF_{EE}$. The spatial relation between the coordinate frame of the end-effector and the optical tool is known, and the transformation between the camera frame and the task frame is obtained. Therefore, the actual pose of the end-effector is $^{R}\boldsymbol{P}_a = (^{R}\boldsymbol{T}_a, {}^{R}\boldsymbol{Q}_a)$, where $^{R}\boldsymbol{T}_a = {}^{C}\boldsymbol{T}_a$ and $^{R}\boldsymbol{Q}_a = {}^{C}\boldsymbol{Q}_a$. Please note that we consider the optical tracking system reference frame in its starting pose (i.e. no translation $^{C}\boldsymbol{T}_a = (0,0,0)$ and no rotation $^{C}\boldsymbol{Q}_a = (1,0,0,0)$), when the robot end-effector is fully retracted. In this case, the robot end-effector can translate along both positive and negative values of x and y axes, but only along positive values of z axis.

The Polaris Spectra is connected to the control workstation through the NI-9871 (National Instruments) RS422 serial interface. The measurement rate for the Polaris Spectra is set to 25Hz.

Control workstation

The control workstation employs a host-target structure composed by a host computer, a real-time controller, and a field programmable gate array (FPGA). The proposed control system architecture is schematically depicted in Fig.4.

The host computer runs Windows 7 (Microsoft, Redmond, WA, USA) and LabView (National Instruments, Austin, TX, USA) to program, operate, and display the graphical user interface (GUI) shown in Fig1c. Through the

GUI the user is able to configure and monitor the robot, and to communicate with the real-time controller. These features are implemented in three parallel loops running at 20Hz. The host computer is connected with the real-time controller (NI-compactRIO 9068, National Instruments Austin, TX, USA) via ethernet and the messages exchange between host and target is handled by the dedicated loops (i.e. "event handling" loop and "GUI message" loop) at 20Hz on both sides.

The real-time controller (667 MHz dual-core ARM Cortex-A9 processor, 1 GB non-volatile storage, 512 MB DDR3 memory) runs the real-time operating system (NI Linux Real-Time OS), and is programmed using LabView real-time. It controls the robot, and exchanges data with the FPGA and the host computer. The real-time controller connects with the FPGA boards (National Instruments, 8-slot Artix-7 FPGA chassis) through direct memory access (DMA, 32 channels), and with the UR10 controller using socket communication via ethernet. The FPGA runs a library (written in LabView FPGA) dedicated to the communication between the high-level control system and the EPOS2 low–level motor controllers. The communication is implemented through the CAN bus protocol and the high speed NI-9853 CAN module (National Instruments) for compactRIO.

Control Methods

Position control of the proposed surgical system is based on a combination of open-loop and closed-loop position controllers [32]. An open-loop control uses individual motor encoders to control the robot's pose (parallel-robot and carrier platform) in the task space. External position measurements are necessary for the overall system accuracy and repeatability: visual feedback is gained by optical tracking data in order to implement closed-loop vision-based control (VBC) on the parallel-robot.

The robot's real-time controller has been designed and implemented as shown in Fig.5. The implementation and evaluation of the proposed control system are described below.

Open-loop control

The open-loop (OL) controller is based on the parallel-robot and UR10 kinematics [33] as shown in Fig.6 and works as follows. The surgeon defines the desired pose for the parallel-robot end-effector $^R\boldsymbol{P}_d = (^R\boldsymbol{T}_d, {}^R\boldsymbol{R}_d)$ through the GUI by interacting with a 3D model of the fracture using the mouse, i.e. virtually reducing the fracture on the screen, by solving the "3D fracture puzzle". The initial and the desired parallel-robot end-effector positions are now defined by solving the inverse-kinematics, first for the UR10 (Fig.6b) for coarse positioning, and then for the parallel-robot for the fine positioning (Fig.6a). From this point, the surgeon does not interact with the system anymore, and the robot executes the fragments' manipulation. The pose is expressed as a translation $^R\boldsymbol{T}_d = (^Rx_d, {}^Ry_d, {}^Rz_d)$ (in mm) of the robot end-effector coordinate frame origin O_{EE} (Fig.6a) along x, y, z axes, and as the rotation $^R\boldsymbol{R}_d = (^Rroll_d, {}^Rpitch_d, {}^Ryaw_d)$ (Euler angles in degrees) of the robot end-effector coordinate frame CF_{EE} (Fig.6a) around roll, pitch, yaw axes. The task space trajectory generator generates a desired trajectory for the robot to reach the desired pose $^R\boldsymbol{P}_d$, while the inverse kinematics calculates the motion commands for the carrier platform arms and for the six struts of the parallel-robot based on the desired end effector pose.

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The inverse kinematics for the UR10 is using Denavit Hartenberg (DH) method; please refer to [33] for an extensive analysis.

The inverse kinematics for the parallel-robot is derived using the loop closure approach for each of the struts (refer to Fig.6a). This is a vector method that gives relationships between the key points of the robot structure, i.e. O the centre of the base platform, O_{EE} the centre of the moving plate and the end-effector, A_i and B_i are the points where each strut i is attached to the base and the moving platform respectively. Their relation is given in (2).

$$\overrightarrow{OO_{EE}} = \overrightarrow{OA_i} + \overrightarrow{A_iB_i} + \overrightarrow{B_iO_{EE}} \qquad \text{for } i=1\ldots6 \qquad (2)$$

The $\overrightarrow{OO_{EE}}$ vector is the desired position of the end-effector in the reference frame of the base platform, vectors $\overrightarrow{OA_i}$ and $\overrightarrow{B_iO_{EE}}$ are known vectors based on the robot's geometry, usually the diameter of the inscribed circle for the plate and the internal angles of the hexagon. Finally, vector $\overrightarrow{A_iB_i}$ is the vector of each strut. By representing each point in its three-dimensional vector form, i.e. (x_n, y_n, z_n) we can calculate the magnitude of this vector using (3).

$$\left\|\overrightarrow{A_iB_i}\right\| = \sqrt{\left(x_{B_i} - x_{A_i}\right)^2 + \left(y_{B_i} - y_{A_i}\right)^2 + \left(z_{B_i} - z_{A_i}\right)^2} \qquad \text{for } i=1\ldots6 \qquad (3)$$

The length values from (3) are the commands delivered to the motion generator system that synchronises the six actuators using a velocity feed-forward control scheme. This is performed by adjusting the axis velocities based on the leading manipulator axis, i.e. the axis performing the slowest motion for a given point-to-point motion step. The velocity profile for each axis is calculated using the following equation:

$$\dot{\vartheta}_i = \frac{\ddot{\vartheta}_{MAX} \cdot t_e}{2} - \sqrt{\left(\frac{\ddot{\vartheta}_{MAX}^2 \cdot t_e^2}{4}\right) - \left(s_{i,e} \cdot \ddot{\vartheta}_{MAX}^2\right)} \qquad \text{for } i=1\ldots6 \qquad (4)$$

where:

$$t_e = \frac{s_e}{\dot{\vartheta}_{MAX}} + \frac{\dot{\vartheta}_{MAX}}{\ddot{\vartheta}_{MAX}} \qquad (5)$$

t_e is the end time of the trapezoidal velocity profile of the leading robot axis; s_e is the maximum axis displacement.

This synchronisation algorithm is essential to simultaneously control all parallel-robot actuators and to ensure that all actuators start and stop at the same time. All the above logic is running on the Control Loop at 100Hz in the real-time controller.

Finally, the synchronised motion data are sent to the FPGA that generates motion CAN data and sends them to the EPOS 2 controller, which controls the linear actuators in the low-level in order to reach the desired pose in the task space.

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Vision-based control (VBC)

Once the desired pose $^R\!P_d$ is reached using the open-loop control, the actual pose of the robot $^R\!P_a = (^R\!T_a, ^R\!Q_a)$ provided by the optical tracker is compared to the desired pose $^R\!P_d$ which generates the pose error $E_P(n) = (E_T, E_R)$.

The translational error component E_T is simply the difference between the desired and the actual end-effector Cartesian positions:

$$E_T = {}^R T_d - {}^R T_a = ({}^R x_d - {}^R x_a)^2 + ({}^R y_d - {}^R y_a)^2 + ({}^R z_d - {}^R z_a)^2 \tag{6}$$

For orientation control, the actual quaternion $^R\!Q_a$ provided by the optical tracker is converted into Euler angles as described in [34]. The actual rotation of the robot can be expressed as $^R\!R_d = (^R\!roll_d, {}^R\!pitch_d, {}^R\!yaw_d)$. Therefore, the rotational error component E_R is:

$$E_R = {}^R R_d - {}^R R_a = ({}^R roll_d - {}^R roll_a)^2 + ({}^R pitch_d - {}^R pitch_a)^2 + ({}^R yaw_d - {}^R yaw_a)^2 \tag{7}$$

When $E_T \leq 0.03$ mm AND $E_R \leq 0.03°$, the robot's pose is acceptable and the target is reached. Otherwise the vision-based system is activated to correct the pose as shown in Fig.5. This system is composed of six proportional and integral (PI) controllers, one for each translation (x, y, z) and rotation (*roll, pitch, yaw*) axis of the end-effector in the task frame. It is based on a PI control law [35] and generates motion commands $^R\!\vartheta = (^R\!\vartheta_x, {}^R\!\vartheta_y, {}^R\!\vartheta_z, {}^R\!\vartheta_{roll}, {}^R\!\vartheta_{pitch}, {}^R\!\vartheta_{yaw})$ to adjust the pose of the end-effector. These motion commands generated by the PI controllers are sent to the inverse kinematics block, then to the motion generator (as described in the "*Open-loop control*" sub-section) at each processing time step n using (8):

$$\vartheta(n) = k_P \times E(n) + k_I \times E_I(n) \tag{8}$$

where:

$$E_I(n) = E_I(n-1) + \frac{E(n) + E(n-1)}{2}\Delta t \tag{9}$$

where $E_I(n)$ is the integral error, k_P is the proportional control gain, k_I is the integral gain, and Δt is the sampling time. In the proposed system the following constants were selected after tuning [36]: $k_P = 50$; $k_I = 18$; $\Delta t = 50$ms. When the VBC system is used, the motion generator system creates new actual velocity profiles for each linear actuator at each processing time n based on the new actual position of the robot end-effector provided by the optical tracker; closer to the desired pose the robot gets, the smaller are both s_e, and the actual velocity of each actuator, as described by equations (4) and (5). This means that the actuators' actual velocity profiles decrease as the robot reaches its desired pose.

Finally, the motion generator output is sent to the FPGA, which transmits the CAN data to the EPOS 2 controller as described in the previous open-loop control section. The above logic is running on the Control Loop at 100Hz in the real time controller.

Evaluation Methodology

The developed vision-based control system was assessed in four experimental setups. First experiments, *Optical tracking validation trials,* assessed the accuracy of the optical tracking system. The optical tools used in this work have been designed and manufactured in-house (i.e. not by the manufacturer of the optical tracking system), as previously mentioned in the "Optical Tracking" sub-section. Although we didn't modify the optical tracker itself, the use of "home-made" (i.e. not certified by the manufacturer) optical tools could potentially affect the accuracy of the tracking procedure. Therefore, validation trials should be conducted to confirm that the tracking accuracy using the "home-made" optical tools is comparable to the one stated by the manufacturer. The experimental setup is shown in Fig.7a.

The second and third sets of experiments, *positioning trials,* assessed the system's performance in terms of *precision* and *repeatability* respectively. In all cases, the targets were pre-defined end-effector's positions. The experiments aimed at characterising the proposed vision-based control system through quantitative measurements of its positioning accuracy and repeatability within the parallel-robot workspace, i.e. ±10mm/±15° along/around each motion axis separately, allowing a comparison between the open-loop and the vision-based control schemes. The metrics chosen for the system validation were the root-mean-squared-error (RMSE) and the maximum absolute error (MAE) measured during positioning accuracy trials; the actual positions (APs) measured during position repeatability trials. A 6-DOF load cell (FTSens by Istituto Italiano di Tecnologia, Italy) mounted on the parallel-robot end-effector was connected to a metal orthopaedic pin (length 10 cm). Two rubber bands were attached to the top end of the pin to simulate the soft tissue and, therefore, force/torque required for fragment manipulation (see Table 1). This ensures that the reported positioning results have been achieved under realistic loading conditions. Force/torque data were also acquired during the positioning trials. The experimental setup is shown in Fig.7b.

The fourth set of experiments consisted of *application trials* that assessed the system's accuracy and repeatability during reduction of a distal femur fracture on ex-vivo porcine model. In this case the target was manipulating a bone fragment to match a second bone fragment (in a fixed position) and reduce the fracture. Also in this case, the metrics chosen for the objective evaluation of the system's reduction performance were the RMSE, MAE (accuracy), and APs (repeatability) measured during repeated reduction trials. The load cell connected to the orthopaedic pin provided force/torque applied during the reduction. The experimental setup is shown in Fig.8.

In both *positioning trials* and *application trials* the optical tracker system measurement rate was set to 25Hz, resulting in a visual latency of 40ms. The maximum velocity of the linear actuators was fixed at $\dot{\vartheta}_{MAX}$ = 2.6mm/s, and the maximum acceleration was fixed at $\ddot{\vartheta}_{MAX}$ = 5.2mm/s².

Optical tracking validation trials

An adapted Sensable® Phantom Omni® haptic device was used as a coordinate measuring machine (CMM) for the validation of the optical tracking system. The haptic device was fitted with a Renishaw 3mm diameter ruby ball probe. A precision-machined plate, with three 8mm diameter ruby ball probes fitted in a triangular configuration, was mounted on the robot (Fig.7a). For each position evaluated, 12 measurements were made (4 for each 8mm ball) in order to establish a precise position of the mounted plate. The adapted kinematic model [37] calculated the haptic device resolution to be 0.12mm. The validation trials performed consisted of moving the robot end-effector between two points and comparing the measurements of the CMM system and the visual tracker. A total of 6 sets of measurement points, with 18 repetitions each, were performed along the main Cartesian axes. The measured parameter is the Cartesian distance of the start and end point of the trajectory as calculated by the measured values of the CMM and the visual tracker. The respective RMSE was calculated and compared with the manufacturer's resolution for the visual-tracker and the above-calculated offset for the CMM arrangement.

Positioning accuracy trials

Two sets of 12 trials were conducted for the open-loop control scheme (first set) and the VBC scheme (second set). 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 0.5 mm (translation), and 1° (rotation). Start and end positions were chosen in order to cover both negative and positive directions (excluding translations along z that can have only positive values) to investigate the positioning accuracy in different areas of the parallel-robot workspace. All positioning manoeuvres were executed individually along and around a single axis per trial. Table 3 summarises the motions investigated. Two trials per axis were conducted obtaining 80 different target poses per translational axis (x,y,z) and 60 target poses per rotational axis (roll, pitch yaw), for a total of 420 targets per set. 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. For the VBC trials, the vision-based controller was first used to perform the robot positioning on each target point, and then the optical tracker acquired the actual final position of the robot end-effector, allowing measurement of the position errors.

Positioning repeatability trials

Two sets of 12 positioning trials were performed for translations and rotations in Cartesian space. For each trial the robot end-effector position was oscillating between two target points with different incremental steps, reaching alternatively each point ten times for a total of 20 target points per trial, i.e. 360 targets per set. The positioning manoeuvres were executed individually along and around a single axis per trial, covering both negative and positive directions (z only positive) to investigate the robot workspace. The first set of trials was conducted using the open-loop control, while the second set used the VBC. Table 4 summarises the parameters of the measuring sequences. The optical tracker was used to acquire the actual position of the robot end-effector at each

target point, allowing the measurement of positioning repeatability as the standard deviation calculated on the actual robot positions at each target point of each trial.

Application trials (fracture reduction)

For this experiment, one set of 50 fracture reduction trials was performed using the robotic system and the VBC scheme on ex-vivo porcine model, as shown in Fig.8. First (Fig.8a), the orthopaedic pin (i.e. P1) was connected to the distal end of the unbroken femur, and an optical tool (i.e. P1T) was attached to track its actual pose during the reduction procedure. A second pin (i.e. P2) was inserted into the proximal end of the bone with an optical tool (i.e. P2T) connected as reference. The relative pose of P1T with respect to P2T was then obtained using the optical tracker, and represented the target point for the robot in order to reduce the fracture, i.e. target point in the unbroken configuration. Subsequently (Fig.8b), the femur was fractured in two parts F1 and F2, in order to have P1 inserted in F1 and P2 in F2. P1 was connected to the robot end-effector and the fragment F1 moved from the current broken pose to the unbroken pose to match fragment F2 using the proposed robotic system and VBC scheme. The optical tracker acquired the actual pose of P1T at the target point, allowing the measurement of reduction accuracy as position errors and reduction repeatability as standard deviations at the target point for each trial.

Statistical Analysis

MATLAB (MathWorks, Inc.) was used to perform the data analysis. We checked the normal distribution of the dataset using the Shapiro-Wilk test [38]. The dataset was normally distributed, and the Student's t-test was used to establish significant differences between measurements [39]. All hypotheses were tested using an alpha level of 0.05.

Results

Accuracy of the optical tracking

The measured mean-squared-error (MSE) for the Polaris spectra resulted in 0.265mm along x axis, 0.308mm along y axis, and 0.448mm along z axis. The measured MSE for the customised Phantom Omni resulted in 0.145mm along x axis, 0.166mm along y axis, and 0.139mm along z-axis. The experimental results of the optical trackers accuracy are summarised in Table 5. For the rest of the results section, the measurements are going to be reported based on the Polaris Spectra optical tracker, with errors and deviations included in the measurements.

System's positioning accuracy

The experimental results from the 24 *positioning accuracy* trials are summarised in Tables 6 and 7. The tables report on the performance metric (i.e. RMSE) obtained with both control systems (OL and VBC) while translating (Table 6) and rotating (Table 7) the robot along/around each axis. RMSEs values are reported for each axis. Translational trials (Table 6) in open-loop show that translations along x axis resulted in a RMSE of 1.78±3.83mm along x; translations along y axis resulted in a RMSE of 1.32±1.03mm along y; translations along z

axis resulted in a RMSE of 0.09±0.08mm along z. These positioning RMSEs were reduced respectively to 0.03±0.01mm, 0.03±0.01mm, and 0.02±0.01mm when using the VBC. Similarly, rotation trials (Table 7) in open-loop show that rotations around roll axis resulted in a RMSE of 0.32±0.11°; rotations around pitch axis resulted in 0.24±0.06°; rotations around yaw axis resulted in 1.85±1.54°. Also in these cases the VBC reduced the positioning RMSEs to 0.02±0.01° for all of three rotation axes. Visual representations of the experimental results are presented in Fig.9. Fig.10 summarises the overall positioning accuracy of the robot comparing the performance of the open-loop control and the VBC in terms of RMSE and average MAE measured during the trials.

System's positioning repeatability

A summary of the experimental results from the 24 *positioning repeatability* trials are presented in Tables 8 and 9. The tables report the average actual positions (APs) of the robot at each desired position. The average is calculated on 10 values per desired pose. Data from the trials demonstrated the system has a high repeatability using both the open-loop and the vision-based control. When using the open-loop control, the standard deviations resulted in ±0.16mm along x, ±0.10mm along y, ± 0.04mm along z; ±0.10° around x, ±0.012° around y, ±0.08° around z. When using the VBC system the standard deviations decreased to ±0.001mm along x, y and z, and to ±0.001° around x, y and z. Representative results from these trials are presented in Fig.11, which illustrates the system's repeatability and accuracy provided, by both the open-loop and the vision-based controller.

The load measured during the positioning experiments resulted in average force of 20.74±0.2N and average torque of 1.97±0.02Nm.

Fracture reduction accuracy and repeatability

Results from the 50 *application trials* conducted on ex-vivo porcine femur are summarised in Table10. The table shows the performance of the system obtained with the VBC while reducing a distal femur fracture in ex-vivo porcine model. The reduction accuracy resulted in a RMSE of *0.09±0.02mm* (translational) and *0.15±0.06°* (rotational) calculated over 50 reductions, and an average MAE of *0.12±0.03mm* (translational) and *0.18±0.04°* (rotational). Repeated fracture reduction manoeuvres resulted in a repeatability of *0.02mm and 0.03°*.

The load measured during the fracture reductions was, on average, *24.51±0.4N* (force) and *2.85±0.6Nm* (torque).

Discussion

This paper reports the work conducted at Bristol Robotics Laboratory to build a robotic system with required accuracy and repeatability for fragment manipulation in joint fracture surgery. Surgical robots impose challenging accuracy and repeatability requirements (see Table 1 and [16]), therefore the use of a parallel-robot is a preferred choice as reported in literature [13, 14, 27]. The proposed system has been designed and developed using a 6-DOF parallel-robot attached to a carrier platform, a control workstation based on a host-target architecture (i.e. a host computer running the GUI, a real-time controller, and a FPGA), and the *Polaris Spectra* as optical tracker. In

order to cover the entire required workspace (Table 1), the carrier platform is used to position the parallel-robot close to a final desired position (coarse positioning, Fig.3a), and then the parallel-robot performs the precise fracture reduction (fine positioning, Fig.3b).

The system's control concept is based on the benefits of merging open-loop control (e.g. high speed) with vision-based control (e.g. high accuracy and repeatability). The concept consists of two phases: open-loop control used to move the robot end-effector in a user-defined pose and the visual-feedback used to close the control loop and consequently achieve a more accurate positioning. The goal of the VBC system is to minimise the pose error of the robot end-effector, aiming for null error. However, the time employed by the PI controllers to minimise the pose error is proportional to the chosen error threshold. Setting the error threshold to be $E_T \leq 0.03$mm and $E_R \leq 0.03°$, guarantees a final error pose much below the fracture manipulation accuracy requirements (see Table 1 and Fig.10) while maintaining an acceptable reduction time. The average correction time for each target point, i.e. the time employed by the VBC to reduce the pose error E_P below the chosen thresholds ($E_T \leq 0.03$mm, $E_R \leq 0.03°$), was 1.56±0.4s. Increasing the maximum velocity profile of the linear actuators can reduce this time. However, for this specific application the measured correction time is more than acceptable, since speed at this range (i.e. seconds) is not essential during a surgical operation that lasts in the range of hours.

The proposed control architecture employs a host-target structure (see Fig.4) using different frame rates depending on the computational time-a critical requirement of this application. The host PC running the GUI implements three different parallel loops running at 20Hz to configure and monitor the robot, and to communicate with the real-time controller. The chosen frame rate is sufficient since the only scope of the GUI is sending/receiving message to/from the real-time controller without doing any computational task. The real-time controller runs the actual Control loop, which is the core of the control system. Here, a higher frame rate is required, i.e. 100Hz, since this loop is responsible for time-critical computational algorithms, i.e. the open-loop and vision-based control algorithms, the inverse kinematics, and the motion generator. The visual feedback loop, (responsible for the data acquisition from the optical tracker), runs on the real-time controller since it is a time-critical loop as well. Given hardware and interface limitation (the optical tracker is connected to the real-time controller via a modified serial interface since USB is usually not supported in real-time applications), the measurement rate for the tracking system was set to 25Hz (a similar approach has been reported in [40]). However, a framerate of 25Hz resulted adequate for our application.

The results from the optical tracking validation experiment show that based on the suppliers resolution error for the Polaris Spectra (0.3mm) all measurements were close to the stated error. This is also the case for the customised Phantom Omni and the calibrated mean error of 0.12mm, with the values measured being marginally above the stated error indicated other parameters affecting the measurements. The calculated optical tracker errors are primarily related to the manufacturing procedures for the tracking objects used for both systems, namely the home-made optical tool for the Polaris, and the ruby balls for the Phantom Omni. This is a parameter that could be associated with the precision of laser-cutting used for the former, and the manual NC milling machine for the latter. Also, for the Phantom Omni, the geometrical estimation of the ball centres from a number of measurements could

contribute a small calculation error in software. Based on these observations we can establish that the precision of the mechanical system is higher than the precision of the optical tracker, thus the latter can be used to implement a vision-based control. With respect to the applications desired accuracy of 1mm (see Table 1) the potential mean error generated by the optical tracking system is not affecting it significantly.

A possible issue related with optical tracking systems is the line-of-sight occlusion, i.e. a direct line of sight between the camera and the optical tools must always be maintained. To ensure safety in the event of short occlusion, the system controller blocks the motor generator and no movement of the robot will occur. Then, an operator can move the camera in a new position in order to restore the direct line of sight with the optical tools, and restart the movement of the robot. Another possible solution (not included in the proposed setup) is optical data fusion with an inertial measurement unit mounted on the robot end-effector for a more robust motion tracking, as described in [41]. However, the presented setup could be used without occlusion in real surgeries, since the connection between the moving plate of the robot (where the optical tool is placed) and the bone fragment is obtained through a metallic orthopaedic pin as described in the "Introduction" section. This configuration creates enough space between the optical tool and the leg of the patient allowing for the required line of sight between the tracking camera and the optical tool.

The experimental setup for robot accuracy assessment (*positioning trials)* was designed to reproduce the actual application requirements (Table 1) applying a load to the robot-end effector (measured average force of 20.74±0.2N and torque of 1.97±0.02Nm) while performing the positioning trials. The results of positioning accuracy experiments demonstrate the open-loop achieves overall translational errors of 1.77mm, and rotational errors of 0.64°. Maximum absolute errors measured during the trials reached, on average, about 2mm for translations and 1.96° for rotations as reported in Fig.10. This is possibly due to the positioning error introduced by the serial manipulator under load (drive backlash). Although, UR10 can lock its joints by engaging mechanical brakes and limiting this issue, VBC is required to actively compensate in real-time the positioning errors due to the serial manipulator, and to achieve the necessary positioning accuracy of less than 1mm (see Table 1). The VBC system resulted (Fig.10) in a positioning RMS error of 0.03mm on translations, and RMS error of 0.12° on rotations, corresponding to a pose error reduction of about 98% on translations and 81% on rotations when comparing the VBC with the open-loop control (overall accuracy corresponding to submillimetric resolution). Also, Tables 6 and 7 demonstrate that the VBC is required to eliminate the interdependencies between the axes of motion emerged when using the open-loop control. Movements along/around a single axis generate position RMSEs along/around the other five axes when using the open-loop control. Especially x and y axes results were affected by movements along/around other axes: e.g. translations along x produced a RMSE of 1.26±0.98mm along y axis; translations along y produced a RMSE of 1.02±0.14mm along x axis; rotations around x axis (i.e. roll) produced translational RMSEs of 1.32±0.52mm and 0.89±0.25mm respectively along x, and y. Again, the VBC resulted in a reduction of these values to a RMSE of about 0.02±0.01mm. The results presented in Tables 8 and 9 show that the system has high repeatability: also in these cases the deviations from the desired targets are in the range of micrometres and micro degrees. Also, these data confirm once again that the VBC can effectively eliminate positioning errors of the open-loop control as can be clearly seen in Fig.11.

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Data from the *application trials* corroborate the findings above. The system (VBC) resulted in reduction accuracy of *0.09±0.02mm* (translational) and *0.15±0.06°* (rotational), and reduction repeatability of *0.02mm and 0.03°* while performing repeated real fracture reductions on a fractured porcine femur (ex-vivo). These results (Table 10) confirm the positioning results obtained in *positioning trials* (Tables 6, 7, 8, 9, and Fig.10). The average forces and torques measured during *application trials* (*24.51±0.4 N* and *2.85 ± 0.6 Nm*) are slightly higher than the simulated ones in *positioning trials*; this is possibly due to the presence of real soft tissues (e.g. muscles and ligaments) around the fracture, which counteracted the reduction movements. However, the loads measured in this experiment are compatible with loads we have measured during real fracture surgeries on live humans [24, 25].

Application trials demonstrate that the VBC system is highly accurate, being able to meet the demanding clinical requirements for joint fracture surgeries (Table 1).

Finally, these experiments demonstrate that the proposed system, with a RMS error of 0.09mm (translations) and 0.15° (rotations), has a higher level of accuracy when compared with other systems for long bone fracture reduction reported in literature. The system proposed by Westphal *et al.* [11], a telemanipulated industrial serial robot for femur shaft fractures reduction, resulted in a residual reduction displacement of about 2mm and 2.9°. This level of accuracy could be sufficient for femur shaft reduction applications but it may not be sufficient for fractures that involve joints. The robotic traction table - again for femur shaft reduction applications - proposed by Warisawa *et al.* [12] presented an average positioning error of 0.57mm and 0.12°, and maximum errors of 2mm and 0.34°. However, this system doesn't seem to be applicable to other fracture types, given its non-invasive configuration for the attachment to the patient. Also, a robot attachment at the distal femur allows more precise control of the fracture fragments and causes less strain to the knee joint, as it does not have to transmit the required high forces and torques. Both Wang *et al.* [13] and Tang *et al.* [14] developed robotic systems for femur shaft fracture reduction based on parallel-robot manipulators. Wang's system resulted in mean positioning error of 1.31±0.45mm (axial discrepancy), 2.43±0.49mm (lateral translation) and 2.26±0.23° (angulation), with maximum errors of 2mm, 3mm, 2.5° respectively [13]. Test performed on Tang's system resulted in a residual deviation of 1.24+0.65mm for the axial deflection, 1.19+0.37mm for the translation, 2.34+1.79° for the angulation, and 2.83+0.9° for the rotation [14]. Both Tang's and Wang's systems don't implement closed-loop position control.

Therefore, it is clear that vision-based control is essential for reliable and safe clinical applications, reducing the positioning deviations to submillimetric scale, and ensuring the required level of accuracy, repeatability and safety for highly demanding procedures like joint fracture surgery.

Conclusion

In this paper, a new real-time vision-based system for fragment manipulation during robot-assisted joint fracture surgery was developed and tested. It consists of a 6-DOF parallel-robot attached to a carrier platform controlled through a dedicated control workstation based on visual feedback provided by a commercial optical

tracking system. The control architecture and strategy were accomplished by merging open-loop control with vision-based control.

Fracture reduction experiments using the robot on ex-vivo porcine femur model were performed to assess the reduction accuracy and repeatability of the system. The experiments revealed that the system has submillimetric resolution when the vision-based control is used, resulting in an overall reduction RMS error of 0.09mm (translations) and 0.15° (rotations), and reduction repeatability of *0.02 mm* and *0.03°*. These experiments also demonstrated that the vision-based system can realise fracture reduction with minimal deviations from the desired target with an average maximum error value of *0.12mm* (translations) and average maximum error of *0.18°* (rotations) when using the vision-based control. This leads to the conclusion that the proposed system is suitable for real joint fracture surgery procedures.

In the next steps of development, evaluation trials will include further experiments on cadavers. A new version of the system will implement a bespoke design of the carrier platform for distal femur fractures and fracture surgery preplanning software. Furthermore, hybrid force-position control will be integrated into the system to enable automatic adjustment of the bone positioning based on force-torque feedback.

Acknowledgements

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Tables

TABLE 1
Fracture Manipulation Requirements

Parameter	Value
Required Translational Accuracy	< 1mm
Required Rotational Accuracy	< 5°
Translational and Rotational Workspace	2mm - 5cm 5° - 180°
Forces/Torques for Manipulating Fragments	~ 20N ~ 2Nm

TABLE 2
Parameters of the robot

Parallel Robot	
Moving Platform Diameter	118mm
Base Platform	135mm
Fully Retracted Strut Length	141.88mm
Fully Extended Strut Length	184.95mm
Workspace (dexterous)	±10.25mm $(x-y)$ ±15mm (z) $\pm17°$ (roll,pitch,yaw)
Load Capacity	360N 12Nm
Robot Weight	29Kg
Carrier Platform (UR10)	
Joint dimensions (see Fig.6b)	$d_1 = 128$mm $a_2 = 612$mm $a_3 = 571$mm $d_4 = 162$mm $d_5 = 116$mm $d_6 = 85$mm
Repeatability	0.1mm
Workspace (spherical)	1300mm (radius)
Load Capacity	100N

TABLE 3
Parameter of the measuring sequences during positioning accuracy trials

Axis	Incremental Step	Starting Point	Ending Point	Number of Targets OL (per axis)	Number of Targets VBC (per axis)
x-y (translation)	0.5 mm	-10 mm	10 mm	80	80
z (translation)	0.5 mm	10 mm	20 mm	80	80
roll – pitch – yaw (rotation)	1 °	-15 °	15 °	60	60

TABLE 4
Parameter of the measuring sequences during positioning repeatability trials

Axis	Incremental Step	First Target Point	Second Target Point	Number of Targets OL (per axis)	Number of Targets VBC (per axis)
x – y (translation)	20 mm	-10 mm	10 mm	20	20
	5 mm	-5 mm	0 mm	20	20
	5 mm	0 mm	5 mm	20	20
z (translation)	20 mm	5 mm	25 mm	20	20
	5 mm	10 mm	15 mm	20	20
	5 mm	15 mm	20mm	20	20
roll – pitch – yaw (rotation)	30 °	-15 °	15 °	20	20
	5 °	-5 °	0 °	20	20
	5 °	0 °	5 °	20	20

TABLE 5
Optical tracker over Coordinate Measuring Machine (CMM) measurements

Measuring System (nominal error)	MSE (mm)		
	X Axis	Y Axis	Z Axis
Polaris Spectra (0.3mm)	0.265	0.308	0.448
Custom Phantom Omni (0.12mm)	0.145	0.166	0.139

TABLE 6
Results from positioning accuracy trials: translations along x, y, z axes

Translation Axis	Control Mode	RMSE x (mm)	RMSE y (mm)	RMSE z (mm)	RMSE Roll (°)	RMSE Pitch (°)	RMSE Yaw (°)
x (n=160)	*OL*	*1.78 ± 3.83*	1.26 ± 0.98	0.57 ± 0.31	0.4 ± 0.12	0.43 ± 0.11	0.23 ± 0.22
	VBC	*0.03 ± 0.01*	0.04 ± 0.01	0.02 ± 0.01	0.03 ± 0.01	0.02 ± 0.01	0.02 ± 0.01
	Reduction	*98%*	97%	96%	93%	95%	*91%*
	p	*0.004*	0.0002	0.0151	0.035	0.003	0.021
y (n=160)	*OL*	1.02 ± 0.14	*1.32 ± 1.03*	0.46 ± 0.35	0.50 ± 0.21	0.34 ± 0.11	0.27 ± 0.11
	VBC	0.02 ± 0.01	*0.03 ± 0.01*	0.02 ± 0.01	0.01 ± 0.01	0.02 ± 0.01	0.03 ± 0.01
	Reduction	98%	*98%*	96%	98%	94%	89%
	p	0.0001	*0.0003*	0.002	0.0018	0.003	0.0133
z (n=160)	*OL*	1.32 ± 0.27	0.39 ± 0.11	*0.09 ± 0.08*	0.34 ± 0.21	0.23 ± 0.18	0.29 ± 0.21
	VBC	0.02 ± 0.01	0.03 ± 0.01	*0.02 ± 0.01*	0.01 ± 0.01	0.01 ± 0.01	0.02 ± 0.01
	Reduction	98%	92%	*78%*	97%	96%	93%
	p	0.018	0.015	*0.051*	0.0135	0.018	0.021

TABLE 7
Results from positioning accuracy trials: rotations around x, y, z axes

Rotation Axis	Control Mode	RMSE x (mm)	RMSE y (mm)	RMSE z (mm)	RMSE Roll (°)	RMSE Pitch (°)	RMSE Yaw (°)
roll (n=120)	*OL*	1.32 ± 0.52	0.89 ± 0.25	0.18 ± 0.05	*0.32 ± 0.11*	0.12 ± 0.07	0.21 ± 0.4
	VBC	0.03 ± 0.01	0.03 ± 0.01	0.01 ± 0.01	*0.02 ± 0.01*	0.02 ± 0.01	0.02 ± 0.01
	Reduction	98%	97%	94%	*94%*	83%	90%
	p	0.0002	0.0006	0.025	*0.0024*	0.019	0.012
pitch (n=120)	OL	1.23 ± 0.56	1.34 ± 0.48	0.21 ± 0.04	0.24 ± 0.12	*0.24 ± 0.06*	0.24 ± 0.5
	VBC	0.02 ± 0.01	0.03 ± 0.01	0.02 ± 0.01	0.02 ± 0.01	*0.02 ± 0.01*	0.02 ± 0.01
	Reduction	*98%*	*98%*	*90%*	*92%*	*92%*	*92%*
	p	0.001	0.002	0.03	0.034	*0.018*	0.02
yaw (n=120)	OL	1.35 ± 0.41	1.24 ± 0.36	0.19 ± 0.06	0.15 ± 0.04	0.14 ± 0.08	*1.85 ± 1.54*
	VBC	0.02 ± 0.01	0.02 ± 0.01	0.01 ± 0.01	0.02 ± 0.01	0.02 ± 0.01	*0.02 ± 0.01*
	Reduction	*99%*	*98%*	*95%*	*87%*	*86%*	*99%*
	p	0.0001	0.0012	0.0004	0.0013	0.021	*0.023*

TABLE 8
Results from positioning repeatability trials: repeated positioning along x, y, z axes

Desired Position (mm)	Average APs (mm)					
	x		y		z	
	OL	VBC	OL	VBC	OL	VBC
-10.00	-8.42 ± 0.11	-10.01 ± 0.02	-8.56 ± 0.04	-10.02 ± 0.02	*n/a*	*n/a*
-5.00	-3.11 ± 0.09	-5.99 ± 0.03	-3.74 ± 0.07	-5.00 ± 0.02	*n/a*	*n/a*
0.00	1.51 ± 0.23	-0.02 ± 0.01	1.14 ± 0.33	0.02 ± 0.01	*n/a*	*n/a*
5.00	3.21 ± 0.12	5.01 ± 0.01	3.95 ± 0.02	4.99 ± 0.02	5.10 ± 0.01	5.00 ± 0.001
10.00	8.34 ± 0.25	10.01 ± 0.01	8.90 ± 0.04	9.98 ± 0.01	10.04 ± 0.04	10.00 ± 0.01
15.00	*n/a*	*n/a*	*n/a*	*n/a*	15.07 ± 0.07	15.00 ± 0.01
20.00	*n/a*	*n/a*	*n/a*	*n/a*	20.08 ± 0.07	20.01 ± 0.001
25.00	*n/a*	*n/a*	*n/a*	*n/a*	25.05 ± 0.01	24.99 ± 0.001
RMSE (mm)	1.69 ± 0.16	0.02 ± 0.001	1.20 ± 0.10	0.03 ± 0.001	0.07 ± 0.04	0.01 ± 0.001

TABLE 9
Results from positioning repeatability trials: repeated positioning around x, y, z axes

Desired Position (°)	Average APs (°)					
	roll		pitch		yaw	
	OL	VBC	OL	VBC	OL	VBC
-15.00	-14.37 ± 0.01	-15.01 ± 0.01	-14.88 ± 0.01	-15.01 ± 0.01	-13.68 ± 0.01	-15.01 ± 0.01
-5.00	-4.91 ± 0.01	-5.01 ± 0.01	-4.51 ± 0.01	-5.00 ± 0.01	-3.39 ± 0.03	-5.00 ± 0.01
0.00	0.08 ± 0.01	-0.01 ± 0.01	-0.10 ± 0.02	0.01 ± 0.01	0.78 ± 0.23	0.01 ± 0.01
5.00	4.63 ± 0.01	5.02 ± 0.01	4.75 ± 0.01	5.02 ± 0.01	3.18 ± 0.02	5.01 ± 0.02
15.00	14.88 ± 0.01	15.01 ± 0.01	14.78 ± 0.01	15.00 ± 0.01	12.36 ± 0.09	15.00 ± 0.02
RMSE (°)	0.33 ± 0.008	0.02 ± 0.001	0.27 ± 0.01	0.01 ± 0.001	1.74 ± 0.08	0.02 ± 0.001

TABLE 10
Results from application trials on ex-vivo porcine femur

	Translational	Rotational
# of Reductions	50	50
Reduction Accuracy	0.09 ± 0.02 mm	0.15 ± 0.06 °
Average MAE	0.12 ± 0.03 mm	0.18 ± 0.04 °
Reduction Repeatability	0.02 mm	0.03 °
Average Measured Load	24.51 ± 0.4 N	2.85 ± 0.6 Nm

Figure Captions

Fig. 1 System setup for robot-assisted fracture surgery composed by: **a** the 6-DOF parallel robot and its low-level controller (EPOS 2), the optical tool and optical markers attached on the robot end-effector (i.e. the top moving plate), and the optical tracker; **b** the parallel-robot connected to the robotic carrier platform (UR10); and **c** the system control software (GUI)

Fig. 2 Required workspace for the robotic system: **a** anterior workspace of ±120°; **b** lateral / medial workspace of ±60°; **c** combined surgical field (spherical section); and **d** robotic system desired workspace

Fig. 3 System workspace: **a** the actual robot workspace (a sphere with radius of 1300mm) containing the desired robot workspace shown in Figure 2d. The two views show the non-reachable work-space in the centre of the sphere (cylindrical section); **b** the workspace of the parallel robot: in grey is the reachable workspace, in green is the dexterous workspace, and in red is the portion of the workspace investigated in the evaluation experiments (±10mm, ±15°)

Fig. 4 Schematics of the control system architecture showing the host-target structure and the control loops (including rates) running on each platform

Fig. 5 Control circuit block diagram: the system compares the actual pose of the robot end effector $^R\boldsymbol{P}_a$ to the desired pose $^R\boldsymbol{P}_d$ generating the error $\boldsymbol{E}_p = (E_T, E_R)$. If the error is not acceptable ($E_T > 0.03$ mm *and* $E_R > 0.03$ °), the PI controller is activated to correct the robot pose

Fig. 6 Kinematic chain for the proposed system: **a** parallel robot: six kinematic chains A_iB_i *(i = 1,...,6)* consisting of actuated linear actuators connect the moving platform to the base plate; **b** carrier platform (image from [33]): the dimensional parameters for the UR10 serial robot are reported in Table 2.

Fig. 7 Experimental setup: **a** optical tracking evaluation: a Sensable® Phantom Omni® device was modified placing a ruby ball probe on its end-effector, and used as a coordinate measuring machine. A measuring plate with three ruby ball probes in triangular configuration was mounted on the moving plate of the hexapod, allowing the coordinate system measurement of the robot end-effector by touching the measuring ball probes with the Phantom Omni ball probe; **b** system positioning accuracy and repeatability evaluation: the parallel-robot performed accurate positioning under the load applied by two rubber bands attached to the orthopaedic pin, and measured by the load cell. The optical tracker acquired the actual pose of the end-effector by tracking the optic markers placed on its top.

Fig. 8 Experimental setup for application trials: **a** orthopaedic pins P1 and P2 inserted in the distal and proximal end of an unbroken porcine femur. The optical tools P1T and P2T provide the relative pose of P1 with respect to P2 in the unbroken configuration, i.e. the target pose for the robot; **b** the femur has been broken in two fragments F1 and F2 connected to P1 and P2 respectively. P1 is then attached to the robot end-effector, and fracture reduced using the robotic system.

Fig. 9 Results from sample positioning accuracy trials comparing the performance of the VBC system to that of the OL system while performing incremental robot end–effector translations of 0.5 mm along x (plot **a**), y (plot **b**), z (plot **c**) axes, and incremental robot end-effector rotations of 1° around x (roll, plot **d**), y (pitch, plot **e**), z (yaw, plot **f**) axes. On the plots, desired positions are marked with *blue solid lines*, the achieved positions in OL with *red dotted lines*, and the achieved positions using the VBC with *green dashed lines*

Fig. 10 Results from system positioning accuracy trials demonstrating the positioning accuracy improvement (translational errors in graph **a**, rotational errors in graph **b**) when using the VBC system

Fig. 11 Sample positioning repeatability trials comparing the performance of the VBC system to that of the OL system while performing ten robot end-effector positioning on desired targets: namely x = 5 mm (plot **a**), y = 5 mm (plot **b**), z = 5 mm (plot **c**), roll = 5 ° (plot **d**), pitch = 5 ° (plot **e**), yaw = 5 ° (plot **e**). On the plots, desired positions are marked with *blue solid lines*, while the achieved positions using the OL and the VBC systems respectively with *red* and *green* "x" symbols