A robot-assisted system for long bone intramedullary distal locking: concept and preliminary results

L. Joskowicz[1], C. Milgrom[2], M. Shoham[3], Z. Yaniv[1], A. Simkin[2]

[1] School of Computer Science and Eng., The Hebrew Univ. of Jerusalem 91904 Israel
[2] Dept. of Orthopaedic Surgery, Hadassah Univ. Hospital, Jerusalem, Israel
[3] Faculty of Mechanical Eng., Technion, and Masor Robotics Ltd., Haifa, Israel
    E-mail: josko@cs.huji.ac.il, WWW site: http://www.cs.huji.ac.il/∼josko

This paper presents a new robot-based system to assist orthopaedic surgeons in performing distal intramedullary locking in femoral and tibial fracture reduction. The system consists of a miniature bone-mounted robot fitted with a drill guide that provides mechanical guidance for manual drilling of the distal screws' pilot holes. The drill guide and the nail's distal locking holes axes are automatically aligned with a few X-ray fluoroscopic images. The goal is to eliminate the guesswork from drill positioning, thus reducing surgery time and surgeon's cumulative radiation exposure, and to ensure drill and hole axis alignment during drilling, thus eliminating geometric errors and their complications. We describe the system's rationale and concept, its architecture and usage protocol, the image processing and registration algorithms, and preliminary experimental results.

1. INTRODUCTION

Closed medullary nailing is currently the routine procedure of choice for reducing fractures of the femur and the tibia [1]. It restores the integrity of the fractured bone without surgically exposing the fracture with a nail proximally inserted in the medullary canal through a minimally invasive opening. The surgeon reduces the fracture by manipulating the proximal and distal bone fragments until they are aligned. He then inserts a guide wire, reams the canal if necessary, and drives the nail in. In most cases, lateral distal interlocking screws are inserted to prevent fragment rotation and bone shortening. The procedure is performed under X-ray fluoroscopy, which is used to view the position of bone fragments, surgical tools, and implants.

Distal locking is recognized as the most challenging step. By repeatedly alternating between anterior-posterior and lateral views, the surgeon adjusts the entry point and orientation of the drill so that its axis coincides with the hole axis (Fig 1). Drilling proceeds incrementally, with each advance verified with new images. Complications include inadequate fixation, malrotation, bone cracking, cortical wall penetration, and bone weakening due to multiple or enlarged screw holes. The surgeon's direct exposure to radiation is 3–30 minutes per procedure with 31-51% spent on distal locking alone [2].
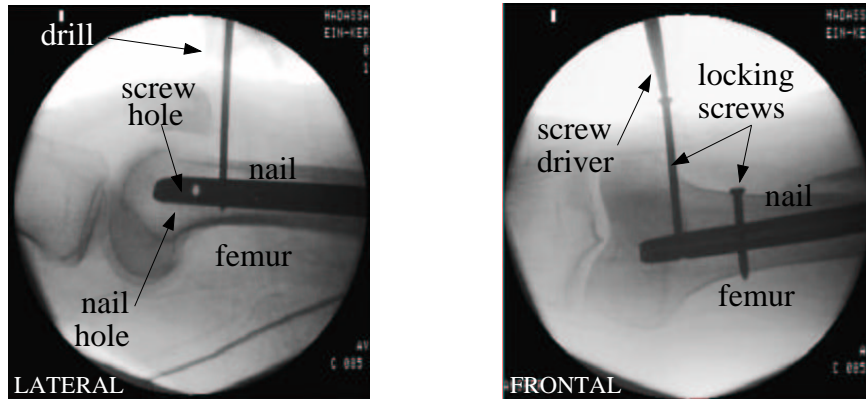
Figure 1. Fluoroscopic X-ray images taken during distal locking, showing the distal femur and the intramedullary nail with its two distal locking nail holes.

2. PREVIOUS WORK

Many devices have been developed for distal locking [3], such as proximally mounted targeting devices, mechanical guides, and stereo fluoroscopy. However, all have drawbacks: they are difficult to use, are not accurate enough, or are not always applicable.

Computer-aided surgical navigation systems [4–6] take the guesswork out of targeting. They enhance, reduce, or altogether eliminate fluoroscopic X-ray images, replacing them with a virtual reality on-screen view in which the bone and instruments' positions are updated in real time as they move. While they can help the surgeon position and orient the hand-held drill at the entry point, they cannot prevent it from slipping and deviating from its planned trajectory as the drilling proceeds.

Robot-based surgical systems mechanically position surgical tools and sometimes execute the surgical action [7]. The robots are floor-standing or table-mounted, adapted or custom serial robots. They are usually bulky and heavy despite the small work load and work volume required for surgery. They require either bone immobilization or real-time dynamic tracking, which complicates the registration procedure and reduces the system accuracy. An exception is MARS, a recently developed miniature parallel robot for drill guiding in spinal procedures [8]. Because of its small size and weight, the robot can be mounted directly on the bone. This robot is the starting point of our work.

3. MATERIALS AND METHODS

Our goal is to develop a system that eliminates the guesswork from drill positioning, thus reducing surgery time and surgeon's cumulative radiation exposure, and to ensure drill and nail hole axis alignment during drilling, thus eliminating geometric errors and its complications. The system should be minimally invasive, easy to use by novice and expert surgeons alike, and require little overhead. The target accuracy is a 1mm positional error at the entry point and 1° axial deviation.

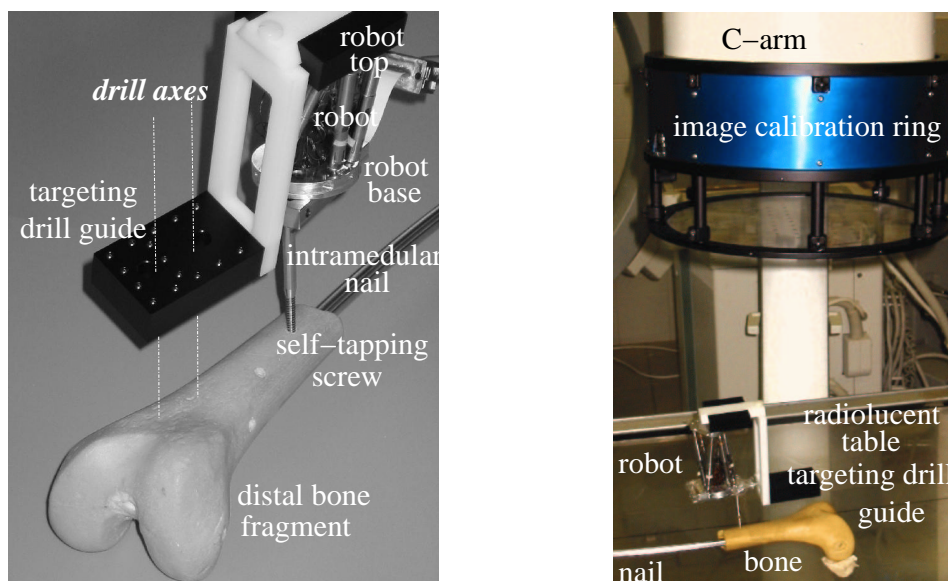Our concept is the automatic positioning of a targeting drill guide with respect to the

Figure 2. Photographs of the robot mounted on the bone and fitted with the targeting drill guide (left) and the fluoroscopic X-ray imaging setup (left).

intramedullary nail holes based on a few fluoroscopic X-ray images (Fig 2). The drill guide is fitted to a miniature robot which is directly mounted on the bone (laterally, distal to the fracture line and proximal to the distal locking nail holes) or on the intramedullary nail's head (via a supporting plate). It provides accurate mechanical guidance for manual drilling. The axes of the distal locking nail holes and the drill guides' holes are brought into alignment by computing the transformation between their initial and final position and positioning the robot accordingly. Mounting the robot directly on the nail or on the patient's bone is minimally invasive, eliminates the need for leg immobilization and real-time tracking, and greatly simplifies the registration.

The system consists of a sterilizable robotically controlled targeting device, an image calibration ring for the fluoroscopic X-ray unit, and a video frame grabber, and a PC computer with a monitor. The targeting device consists of a miniature robot (MARS), a base to attach it to the bone, and a targeting guide mounted on the robot top. The MARS robot is a $50 \times 50 \times 70 \text{mm}^3$, 150–gram six-degree-of-freedom parallel manipulator whose work volume is several centimeters. Its positional accuracy is better than 0.1mm and when locked is very rigid and can withstand several kilogram forces.

The targeting guide is mounted on top of the robot. It consists of a head, a connecting block, and a targeting drill guide. The stainless steel head is mounted directly on the robot top. Its location along the bone long axis can be adjusted manually at prefixed lengths in the 40-80mm range. The connecting and the targeting drill guide are made of radio-lucent Delrin. The targeting drill guide is a $40 \times 55 \times 15 \text{mm}^3$ block with two guiding holes 30mm apart, which is the spacing between the nail holes. It is parallel to the robot base and is close to the patient skin. It has a pattern of 32, 2mm stainless steel fiducial spheres that are used for its spatial localization.
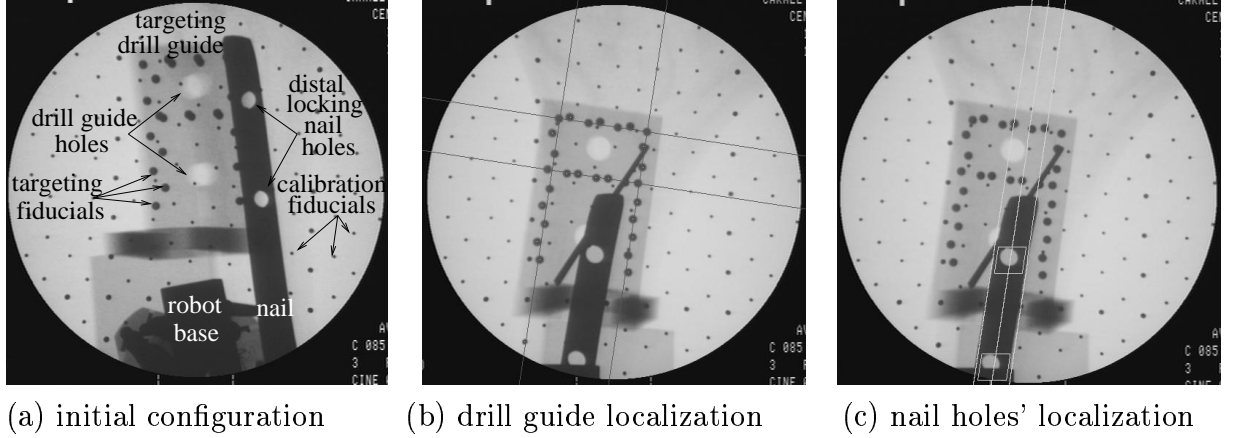
(a) initial configuration   (b) drill guide localization   (c) nail holes' localization

Figure 3. Fluoroscopic X-ray images showing: (a) the targeting drill guide and the intramedullary nail's distal end with its locking holes, (b) the two orthogonal pairs of parallel lines that locate the targeting drill guide, and; (c) the two parallel lines that locate the nail longitudinal contours, and the two parallelepipeds windows that locate the nail holes.

The surgical protocol is as follows. Once the fracture has been reduced and the nail has been inserted to its final position, the image calibration ring is mounted on the C-arm image intensifier. With a distal lateral fluoroscopic X-ray image showing the distal locking nail holes, the surgeon determines the location of the self-tapping screws on which the robot will be mounted. Their axes should be roughly parallel to the distal nail holes' axes and several centimeters proximal to them. The surgeon then drills, with a hand-held jig, two parallel pilot holes at 30mm distance along the axis of the nail. The self-tapping screws are then fastened and the robot targeting base is mounted on it. The targeting drill guide is then mounted on the robot top, and its position relative to the distal locking nail holes is roughly adjusted. With the guidance of the computer, the X-ray technician then adjusts the C-arm orientation to achieve a fronto-parallel view in which the distal locking nail holes appear as circles (and not ellipses) in the image.

The computer software then performs camera distortion correction and calibration [9], and determines the relative position of the targeting drill guide with respect to these holes' axes and computes the transformation that will make the targeting drill guide holes' axes and the distal locking nail holes' axes coincide (Fig 3a). The robot controller then moves the robot by the computed transformation and locks its links into position. The surgeon inserts a K-wire in each drill guide hole and verifies with a new pair of fluoroscopic X-ray images their alignment with respect to the distal locking nail hole centers. The surgeon proceeds to drill the pilot holes, removes the robot from its base and its screws, fastens the locking screws, and completes the surgery according to the standard protocol.

The targeting drill guide is localized by identifying its fiducials and their pattern (Fig 3b). Individual fiducials are identified with the Hough transform: first the fiducial circles are identified, and then their centers is precisely located using followed by Normalized Cross Correlation [10]. The major and minor axes of the targeting drill guide

pattern are then determined from the fiducial locations using Principal Component Analysis. The location of the distal locking nail holes is found by first locating the nail's longitudinal contour with the Canny edge detector and then locating its holes from their expected position with respect to the contour (Fig 3c). The search for the holes is confined to the strip defined by the nail contours and by sweeping in it a parallelepiped window whose sizes are equal to the nail width.

The rigid transformation between the drill guide holes' axes and the distal locking nail holes' axes is computed as follows. Since the targeting drill guide is pre-calibrated, the transformation from the robot's coordinate system to targeting guide is known. The transformation between the targeting drill guide and the C-arm focal point is determined from the extrinsic camera parameters and the known geometry of the targeting drill guide. The system first orients the robot so that the drill guide holes' axes and the camera axes are aligned and then translates the targeting drill guide holes' until the drill guide holes' axes and the distal locking nail holes' axes are aligned.

4. EXPERIMENTAL RESULTS

We have built a prototype of the entire system, which consists of a MARS robot with its controller (Masor Robotics Ltd, Haifa, Israel), a FluoroTrax C-arm calibration ring (Traxtal, Canada), a Matrox Meteor II digital frame grabber, a standard PC, and custom-designed targeting guide and robot mounting base as described above. Fluoroscopic X-ray images were acquired with a 9" BV29 C-arm (Phillips, The Netherlands) and are 800x600 pixels, 8-bit gray-scale with pixel size of about $0.5 \times 0.5mm^2$ in typical imaging setup. We have implemented the software fluoroscopic X-ray image distortion correction and calibration, holes identification and axes computation, robot localization, and registration.

We designed and conducted experiments to test the accuracy and robustness of the different system components. The MARS robot positional accuracy is 0.1mm or better, which is by far sufficient. On-line fluoroscopic X-ray image distortion correction and calibration can be achieved to a mean accuracy of 0.3mm (0.6mm worst case), even in the presence of anatomy and surgical instruments [9]. Fiducial and hole center spatial location can be obtained with a mean accuracy of 0.2mm (0.35mm worst case). The registration process yields a worst-case deviation of 1.5mm and 2 degrees between the drill guide axis and hole axis at the screw entry point, which is considered acceptable.

5. CONCLUSION

Precise drill positioning and guiding with a bone-mounted miniature robot has the potential of significantly simplifying long bone distal locking. By mounting the miniature robot directly on the intramedullary nail or on the bone, no leg immobilization or real-time tracking is necessary. The mounting is minimally invasive and does not require great accuracy. The guesswork of drill positioning based on repeated X-ray fluoroscopy is eliminated, and the mechanical guidance prevents slippage and deviations from the planned trajectory as the drilling proceeds. The time required to mount the robot on the bone, mount the calibration ring on the C-arm, and acquire the images is usually shorter than the time required for trial and error positioning. It is expected to be offset by the benefits of precise mechanical guidance and complications reduction. We believe that the

system has advantages over navigation systems, which require a lengthy setup and do not provide mechanical stability, and over existing robotic systems, which are bulky and require bone immobilization or real-time tracking.

We are currently conducting overall accuracy in-vitro experiments and planning a cadaver experiment. With minor modifications, the system can also be used for the tibia and for retrograde nailing. A similar concept is being developed for spinal pedicle screw insertion [8].

Acknowledgments

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