3D Robot Assisted Fracture Reduction

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Abstract. Reduction in femoral shaft fractures may be difficult to achieve with minimal invasive techniques. Malalignment and high intraoperative radiation exposures can result. Our hypothesis is that robot assisted fracture reduction may improve the quality of reduction while reducing the amount of radiation exposure. In this paper we present a telemanipulator system for the robot assisted reduction of femoral shaft fractures. The telemanipulated reposition is performed with a 2D input device with haptic feedback based on 3D imaging data which can be acquired intraoperatively. With this system, we performed a test series to measure achievable reposition accuracies on artificial broken human femur bones without soft tissues. Furthermore, we performed first tests for the 3D reposition on complete human legs. The experimental set-up and results are presented in this paper. We could show, that the 3D telemanipulated reposition of such fractures is possible yielding very good accuracies in an intuitive and efficient way. Robot assisted fracture reduction has the potential to improve the reposition accuracy and furthermore reduce the X-ray irradiation exposure to patient and OR staff.

1 Introduction

Fractures of the femoral (thigh bone) shaft are nowadays often treated with a minimally invasive technique, called intramedullary nailing. The fracture fixation is achieved internally by a so called intramedullary nail, which is usually inserted from the hip end side of the leg into the bone’s medullary cavity. This technique has proven high union rates between 90-99% with a low incidence of infection [1, 2].

However, several problems associated with this technique have been outlined in literature. E.g., the radiation exposure to the operating staff and to the patient is quite high, especially during the process of reduction with average image intensifier usages between 158 and 316 seconds as recorded in the open literature [1, 3]. A second well-known and meaningful problem is
the malreduction. Significant malalignment in the sagittal and frontal plane differs between 2 and 18 percent [4, 5]. Correct rotation around the shaft axis is difficult to achieve intraoperatively, as only 2D fluoroscopy is used for assessment (see figure 1). Differences of more than 10° of rotation are recorded with an incidence of more than 40 percent [5]. Malreduction leads to unphysiological conditions with consecutive reoperation in several cases [6]. Both problems are related to difficulties in achieving and maintaining the correct reduction. These problems are evident in the femur because of its tube-shaped bony anatomy and its counteracting muscle strength.

In our interdisciplinary working group of engineers and physicians, we are investigating and evaluating methods to overcome these clinical problems, by the use of robot assistance systems.

1.1 Previous Work

In our first studies, we evaluated the reposition performance of a telemanipulated fracture reduction robot in a simplified laboratory set-up. We used CCD cameras instead of X-rays for the fracture imaging and the reduction was performed on plastic bones with artificial fractures without any soft tissues [7] and counteracting forces. The results of these preliminary studies encouraged us to further develop the method of robot assisted fracture reduction because of its intuitive, well controlled, and gentle reposition procedure.

Our second step was to transfer the laboratory set-up a step further towards the real clinical environment. Using human specimens and the combination of X-ray imaging and navigation, we performed tests as close to clinical practice as possible [8]. We could show, that robot assisted fracture reduction is possible in this environment yielding accuracies, which are as good as achievable with conventional methods but conspicuously reduce the amount of required X-ray irradiation time. Unfortunately the achieved reposition accuracy was not better than achievable with the conventional manual procedure due to the poorer quality of the X-ray images, compared to CCD camera images. So one could conclude from these tests that telemanipulated fracture
reduction based on 2D X-ray imaging is possible and conspicuously reduces X-ray irradiation but does not improve the accuracy of reposition. Figure 1 shows some X-ray images from that test series, it can easily be imagined, that the rotation around the bone axis is difficult to reconstruct, figure 1c illustrates the problems arising for correctly reconstructing the bone segment orientations in lateral views.

In this paper, we present our set-up for telemanipulated, robot assisted fracture reduction based on intraoperative 3D imaging of the fracture. The results from a first test series are also presented and discussed in the context of possible benefits for patients and surgeons from a robot assisted fracture reduction procedure.

1.2 Related Work

Robot assisted reduction and fixation of femoral shaft fractures was first described by Bouazza-Marouf et al. [9]. They declared requirements for a reduction tool, but however, they did not publish any experimental results. While there is a world wide copious work and research on many aspects of robot assisted minimally invasive surgery, only few research is done in the field of robotized fracture reductions.


2 System Overview

Our telemanipulator system comprises standard commercial sub systems. As manipulator we use the Stäubli RX 90 (Stäubli Tec-Systems, Faverges, France) robot with its CS7B controller unit programmable in V+. Attached to the robot’s hand is a force torque sensor (FT Delta SI-660-60; Schunk, Lauffen, Germany). Intraoperative 3D imaging is achieved by the Siemens Siremobil Iso C 3D (Siemens AG, Medical Solutions, Erlangen, Germany) fluoroscopy device. For the 3D tracking of the fracture segments and for the registration of the 3D image volume, we use an optical surgical navigation system (VectorVision, BrainLAB, Munich, Germany). The input device, a force feedback joystick (Microsoft®; SideWinder® ForceFeedback 2; Microsoft Corp., USA), is connected to a standard PC (Pentium® 4, 2.8 GHz) running Microsoft® Windows® 2000. All four sub systems (controller PC, robot controller, navigation system, and fluoroscope) are connected via a TCP/IP 100Mbit network. Figure 2a illustrates this telemanipulator set-up.
3 Telemannipulator Reposition in 3D

The process of 3D fracture reduction is separated into two steps. The first step is the acquisition of the 3D data set and the reconstruction and registration of a 3D surface model, which is subsequently used for displaying a 3D scene on the controller PC. The second step is the reposition process itself.

At first, a 3D DICOM data set is acquired with the Siemens Iso C 3D. The BrainLAB navigation system calibrates this data set by computing the rigid transformation from the DICOM coordinate space to the Y DRB (dynamic reference base of the optical navigation system) which is rigidly mounted to the proximal (hip side) femur segment. The DICOM data set and the calibration matrix are transferred to the controller PC. With a simple threshold based segmentation method, the two major fracture segments are segmented and 3D surface models are reconstructed using the marching cube algorithm. The controller PC finalizes the calibration by computing the rigid transformations between the proximal 3D model and the Y DRB and the distal (knee side) 3D model to which the T DRB is rigidly connected. The bone axis is computed using an adapted kind of hough transformation, accumulating all possible orientations of axes, perpendicular to the surface normals of the bone meshes. See [14] for further details.

During the reposition process, the controller PC presents a 3D scene to the surgeon where the 3D models of the proximal and distal fracture segments are displayed accordingly to their real position as measured by the navigation system (see figure 2b).

In our telemannipulator system, the complex 3D reposition problem is reduced to simpler 2D repositions. With a 2D input device, the surgeon can manipulate the fracture intuitively within a 2D projection of the 3D scene. This simplifies the spatial cognition required to successfully reduce fractures. Using an additional switch at the joystick (see figure 3), the user can pan the viewing direction around the bone axis, which enables him to examine and manipulate the fracture from every desired angle. The coordinate system in the distal fracture center (Dist) is the task frame i.e. tool center point for all
manipulations. It is oriented in a way, so that the y-axis is pointing knee wards and the z-axis upwards. For translational motions, the mapping between the joystick axes and the movement vector in task space is quite easy. The joystick’s left/right axis is directly mapped to motions along the task frame’s y-axis. The joystick’s front/back axis is mapped to a motion vector in task space, which is created by the cross product between the viewing direction and the task frame’s y-axis and so results in movements perpendicular to the bone axis but inside the image plane. The mapping between the joystick and the corresponding motion in task space can be expressed as a homogeneous transformation matrix $\text{Joy}_T^{-1}\text{Task}$. For rotational manipulations, the joystick’s front/back axis is mapped to rotations about an axis parallel to the viewing direction going through the task frame, whereas the left/right axis is mapped to rotations about the task frame’s y axis, i.e. the bone axis. In this way all required rotations in 3D can be intuitively achieved by rotations inside the image plane.

The force feedback capabilities of the joystick are used to reflect the forces acting during contacts between fracture segments and the forces of soft tissue interactions back to the user. With $\text{Joy}_T^{-1}\text{Task}$ the forces measured in the task frame can be transformed into the joystick’s force feedback axes to which they are applied as constant force values scaled down to an appropriate range.

Figure 4 illustrates the signal flow in our system. The force/torque sensor is read out at a constant rate of 50 Hz and the joystick position with 30 Hz. The desired feedback force of the joystick is also updated with a rate of 30 Hz. The force feedback control itself is accomplished directly inside the control system integrated into the joystick. So we have a maximum delay for force feedback of about 50 ms. Robot position set-points are generated at a rate of 10 Hz. Due to our non-real-time operating system and the non-deterministic communication between the PC and the robot control unit, these rates are not absolutely stable. However, due to the low stiffness of the environment (see section 5) and the force based speed reduction (see next passage), the system performed so far always safe and reliable.
The force based speed reduction module of our processing chain prevents the surgeon from applying forces that are too high for the robot and/or the patient. If the angle between the force and motion vector is larger than 90° and the force value exceeds a predefined threshold, the motion vector will be scaled down linearly with the force until it is set to zero when the force exceeds a second critical force threshold. If the angle between the force and the motion vector is less than 90° the motion command will be executed without any scaling. In this way it is always possible to drive the robot safely out of high force contact situations.

4 Experiments

As a first step in evaluating the performance of our 3D telemanipulator system, we performed a test series with real human bones. The soft tissues of the bones have been removed and a fracture has been placed by means of a three-point-bending. We chose to use real bones and not plastic bone models because of their more natural fracture surface, which conspicuously complicates the process of reduction.

Four test persons repositioned one fractured bone several times in order to perform a learning curve with this new telemanipulator system. Subsequently they repositioned eight further bones each twice to perform the measurements in order to evaluate the reposition parameters. We measured the reposition time and the remaining translational and rotational deviations after the reposition with respect to the unbroken reference state.

The set-up for our measurements is similar to the one we had used for our 2D test series previously published in [8]. First the two DRBs are mounted to the unfractured bone and the relative transformation from the hip to the knee side is recorded by the navigation system. Now the DRBs are removed from their sockets to avoid displacements during fracture placement. A brake point was sawn and the bone was broken by means of a tree-point-bending. Subsequently the DRBs were remounted in the same position to the bone.

Fig. 4. Signal flow diagram of our telemanipulator set-up.
After these preparation steps, the fracture was repositioned with the robot used as a telemanipulator as previously described in section 3. When the operator decides to finish the reposition process, the remaining deviations from the original reference position was recorded.

The test set-up for reposition using human specimens is identical to the one used for bare bones. By the time of writing this article, we have just performed some initial reposition tests and have not yet completed a whole test series. But these initial tests showed the problems arising due to forces introduced by the soft tissue. A direct movement into the target position is often not possible, due to forces exceeding a maximum threshold. So the reposition strategy has to take some knowledge of how forces are introduced by the soft tissue into account as well.

As stated in our conclusion below, the long term goal of the project is a (semi-) automated fracture reduction by the robot. Of course, such an automated reposition should be force/torque guarded/guided. Therefore we examined the forces which act during common reposition situations, namely lateral contact, lateral distraction, axial contact, axial distraction, and axial rotation in contact. All these situations have been tested with intact soft tissues and the proximal femur loosely fixed to the OR table with a noninvasive, non-obstructive belt. We measured the forces and force/way ratios as well as the displacements of the proximal femur due to the acting contact/distraction forces.

5 Results

In the case of bare bones, we found out, that the learning curves for the users are very steep. After a first introductory reposition, we couldn’t find any further learning effects regarding reposition time and accuracy in all test persons. And even throughout the rest of our test series, we couldn’t find any learning effects. The achieved accuracies have been on a high level starting with the first reposition. It turned out that such a 3D telemanipulated reposition procedure is very intuitive for the surgeons. So far, we haven’t performed enough repositions with intact soft-tissues to measure learning effects in a more realistic environment.

The experiments with bare bones achieved very good results with deviations of less than two degrees and two millimeters in the mean. Compared to clinical results achievable manually, these values are very satisfactory. Table 1 summarizes the results in detail.

Figure 5 illustrates some of our results obtained from force/motion measurements on human bones with intact soft tissues. From the five contact states mentioned before, we will limit the presentation here to the one with the most conspicuous results, which is the movement from a slight distraction of the bone fragments into contact. The diagram on the left presents the forces acting in the direction of the bone axis which was moved into contact. It is remarkable, that even though the bone moves from distraction into contact, the force/motion profile is almost linear. The reason for this is the motion of the
proximal femur part, caused by the continuous decrease of distraction forces of the soft tissues. The overall stiffness of the system is about $k = 9.5 \text{ N/mm}$. The discontinuities at the end of the motion sequence are the result of some jerky movements of the proximal leg due to the high forces.

The diagram on the right side of figure 5 illustrates, how motions of the robot, i.e. the distal segment attached to it, affect the proximal femur and the fracture displacement. Two points are of interest in this diagram. First it is notable, that the major part of the robot motions is almost directly and linearly reflected by the proximal femur. Secondly, from the fracture displacement curve, we can state, that the contact is established after approximately 6 mm of robot motion, whilst the contact force measurement would establish a contact at the zero-crossing after 11 mm. From this we can conclude that a contact situation can not be identified by force analyses only. This has to be taken into account when developing automated reposition procedures.

### 6 Conclusion and Outlook

The user interface for telemanipulation proved to be very efficient and intuitive. All test persons could reduce fractures successfully after a very short training. The only difficulty stated by the surgeons is to remember the mapping between left/right alignment of the joystick and the corresponding rotation around the femur shaft axis. But we think, this problem can be addressed.
by simply visualizing the direction of rotation by means of some arcs within the 3D scene.

The reposition results achieved during our tests (reposition time and accuracy) are very promising and show the potential of robotized fracture reduction based on 3D imaging data. However, in this study we only had two-part fractures. It is still to be shown, how telemanipulated reductions perform if there is no complete connection between the proximal and distal segment (complex fractures, see figure 1c). Maybe only an automated computation of the desired goal position as stated in our outlook can bring the desired accuracy for those fractures. The next steps will be to evaluate the set-up on fractures with intact soft tissues.

Due to the usage of a non real-time operating system and LAN communication with a standard commercial controller, the performance of our feedback loop is not very efficient. The usage of a real-time operating system on the controller PC in combination with the new robot control architecture developed at our institute [15], could conspicuously improve the performance of the telemanipulator system. But however, the existing non-real-time system, as it is currently used for our tests, performed absolutely reliable in all situations. As even in contact situations the stiffness of the system is quite low and the force based speed reduction module allows a careful approach to the contact, the slow control rates of our system have not been a problem so far.

After finishing the experiments with telemanipulated repositions in human specimens, the next step in our working program will be the automated fracture reduction by the robot. Based on 3D CT data sets, we developed methods to automatically compute the desired reposition parameters for fractured long bones [14].

To conclude the robot assistance for this surgical procedure, we have already developed methods to support two more procedure task, which can obviously benefit from robot assistance. The insertion of the intramedullary nail at the hip side of the leg and the nail locking at the knee side. Both methods use automated computer vision methods to enable a robotized drill guidance. These methods are currently under testing in cadaver studies.

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References