Surgeon-instructed, Image-guided and Robot-assisted Long Bone Fractures Reduction

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Abstract

Bones are dynamic structures, being supported by muscles, tendons, and ligaments. When some or all the structures are disturbed i.e. in fractures, the alignment of the bone in respect to the rest of the body is deranged. This gives rise to axial as well as rotational deformity in three dimensional planes. The correct alignment and position of the long bones are to be maintained to heal the bone in the best possible anatomical and functional position. The objective of this research is to address the problems in the current practice involving surgeon, assistant, fluoroscopy and crude mechanical means and to see if a robotic solution exists to solve the problems of manipulating and reducing long bone fractures. This paper presents various design aspects of the proposed surgeon-instructed, image-guided and robotic system including the system design specification, robot design and analysis, motion control and implementation, and x-ray image processing and incorporation in CAD environment.

Keywords: Orthopaedic robot, platform robot, bone fractures reduction, image processing

1 Introduction

Using computer assisted or robotic surgery for doing orthopaedic procedures is a concept which is still in its infancy. Unlike industrial robots, medical robotics and particularly orthopaedic robotics and CAOS (Computer Aided Orthopaedic Surgery) are still much in the design and inception phase. Most of the developments in the field have happened in the last 10 years or so and only now some of the robotic devices are being allowed for clinical trials [1].

As is quite evident from the different studies the main emphasis of CAOS and robotics in Orthopaedics has been in relation to specific application. Specifically in total hip and knee arthroplasty robots have been used for specific tasks. In hip replacement, ROBODOC®, one of the earliest systems developed, works as a precision milling device for the preparation of the femur [2]. CASPER developed in Pittsburg is another device almost similar to ROBODOC. For knee arthroplasty ACROBOT® (Armstrong Healthcare) a robot developed in the imperial college London helps the surgeon to make precise bone cuts for the knee arthroplasty. One of the other major areas where robotic surgery is being researched for applications is spine and pelvic surgery. Especially in the realm of spine surgery pedicle screw placement requires very exact positioning and CAOS allows that [3]. Other areas where CAOS has been researched are pelvic osteotomies, ACL reconstructions, and radial osteotomies [4].

What is the reason for orthopaedic surgery to be a hotbed for so much robotics and computer assisted research? The answer can be found in the basic physical properties of bone. Bone has definite rigid structure and dimensions and behaves very predictably in the clinical setting. If a bone fractures the fragments displace in a certain predictable way. Also the bony framework being rigid, anatomical landmarks can be determined easily and imaged without much difficulty [5]. But because of the immense variation in the type of bony trauma, researches for trauma related orthopaedic application have been limited to specific aspects of trauma surgery.

There are specific areas of trauma where research is going on. These include pelvic fractures[6] and spinal fractures[7]. The one specific area is long bone fractures, specially femur and realignment during intramedullary nailing. Kinematic models of long bones such as femur, have been designed based on an external fixator scenario to reduce long bone fractures. In [8] a model for reduction based on an Ilizarov type fixator has been proposed. Because of the fixator being fixed to the bone in a three dimensional plane, the proposed device would be able to reduce the fracture accurately. In [9] tibial fracture reduction was proposed, where they proposed a bone reduction simulation programmed called SERF (Simulation Environment of a Robotic Fixator), in relation to an Ilizarov fixator. Huffner [10] showed that in a simulated fracture environment, direct reduction of fracture and computer simulated fracture reduction was, overall very small. Daniel Schmucki et al [11] from AO Institute in Switzerland have described work that has been going on in Europe whereby computer modeling of fracture reduction is being done in a virtual environment. Studies are also going on in terms of virtual computer based reduction based on fluoroscopy and CT scan.

One aspect of long bone fracture has received considerable attention. This is placement of distal locking screw in intramedullary nailing of long bone fractures as most of the time this procedure is done without any aligning jig, and dependent on the experience of the surgeon and alignment of the fluoroscope. Suhm et al [12] did a study on 42 intramedullary nail distal locking and they found that computer based surgery reduces radiation exposure and increases accuracy. The drawbacks were the complex procedure and increased procedure time. In Hebrew University in Jerusalem, Leo Joskowicz and team is developing FRACAS(Fracture Computer Aided Surgery) [13,14] which will aid in intramedullary nailing of long bone fractures. In this aspect a small bone mounted robot has also been proposed to help in distal locking. Manipulation of fractured bone using a telemanipulator has also been seen to give very accurate reduction [15].

There have been a few studies outlining methods to perform internal fixation of fracture neck of femur. Bouazza-Marouf et al [16] described a device to manipulate and position a guide wire insertion device to drive a guide wire into the head of the femur. ORTHOSISTA™ (Armstrong Projects Ltd) is a robotic system which has been developed to insert guide wires for the head of the femur [17]. This is basically a four degree-of-freedom active robotic localizer with double Cartesian articulation offering rigidity. This robot uses fluoroscopy to register the images and the surgeon decides the trajectory by guiding the path on an Anteroposterior (AP) and Lateral (Lat) plane fluoroscopic image. The robotic controller then computes the 3D geometry and kinematics necessary to compute the necessary robot motion.

Recently a robotic device has been described in [18], which uses a modified industrial robot, a Stäubli robot (model RX130) for reducing and maintaining femoral fractures. This works by the robot being attached to the shaft of the long bones with external fixator pins which is gripped by the robotic device by a two fingered gripper. A force feedback sensor relays the forces and moments in all three axes. This reduction system worked in an artificially simulated fracture scenario and reduced fracture and maintained reduction adequately.

The robotic system that we conceptualized has not been looked into by any of the research groups working in fracture robotics. The choice of the robot itself was novel, parallel robots itself was used infrequently in medical robotics, though some use of parallel robots are described in Rehabilitation robotics [19]. The problem statement that we started our research was to find three main solutions: firstly, to find a better, alternative traction manipulation device than we have now (see Figure 1); secondly, to supplement and complement surgeon skills in manipulating and reducing fractures; and thirdly, to look into the future of fracture surgery and design a smart "tool" for the future. The research was aimed at developing a surgeon-instructed, image-guided and robot-assisted surgical system.

Figure 1: Current practice of fracture realignment

2 The Proposed System

2.1 Overview

The proposed semi-automated surgical system is illustrated in Figure 2. The surgeon plans an optimal trajectory of fractures realignment on the PC where the robot model and the bone model reconstructed from a few X-ray images reside in the same software environment, i.e. SolidWorks and Cosmos/Motion in this study. This is a planning phase. The motion commands generated by the planned trajectory are passed to the robot to actually move the fractured bones that are attached onto the top plate of the robot. This is an operation phase. The actual motion and forces are fed back for closed-loop position and dynamics control of the robot.

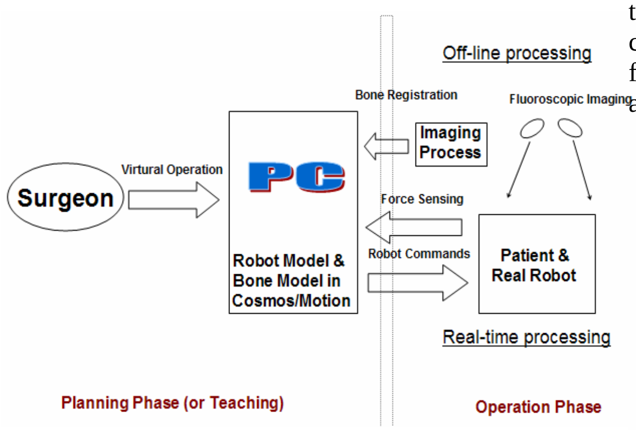


Figure 2: Overview of the proposed robot system

2.2 Force Acting on Femoral Shaft

The main problem with long bone fracture reduction is the deforming forces. The long bones usually have soft tissue attachment throughout the length of the bone. These include muscles, tendons and ligaments. All these when the bone is fractured causes deforming forces at the fracture site, thus deforming the fracture fragments. The deforming forces and the final deformity depend on the site of fracture and the attachment of soft tissues in that area. Even though the exact forces acting on the fracture fragments are difficult to determine, most of the time the attitude of the fragment can be predicted with accuracy, by knowing the line of action of the muscle forces acting on the bone.

Taking the femur as example, the biggest long bone, and the one with the most complex post fracture deformity is the easiest demonstration of the fact. In the case of a proximal shaft of femur fracture, as illustrated in Figure 3, the deforming forces of the gluteal muscles which attaches itself to the greater trochanter, pulls the proximal fragment to an abducted position. This proximal fragment is also flexed and externally rotated by the action of the iliopsoas muscles on its insertion on the lesser trochanter.

In case of the midshaft fractures, apart from the previously described muscle forces, the adductors are attached spanning the whole length of the shaft, and exert an adduction component to the distal fragment, causing even more displacement between the fragments by causing an axial and varus pull. If the fracture line runs through the supracondylar area, the gastrocnemius muscle flexes the distal fragment to cause an angular deformity (see Figure 4).

As is evident from this example, the deforming forces and the resultant deformity can be pretty complex in a femur fracture but can be predicted by the nature of the injury. In the case of a femur fracture sufficient amount of force has to be generated to overcome the deforming forces. It has been shown by studies that, up to 240N of tensile force is required to reduce femur fractures[1]. In case of the other long bones especially the tibia, the forces are governed by gravity as distally the muscle attachment is much less.

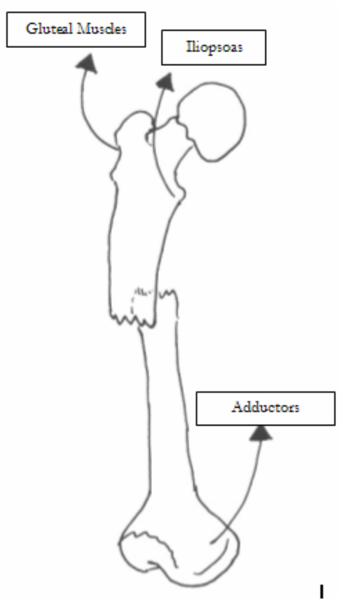


Figure 3: Force acting on a femur fracture

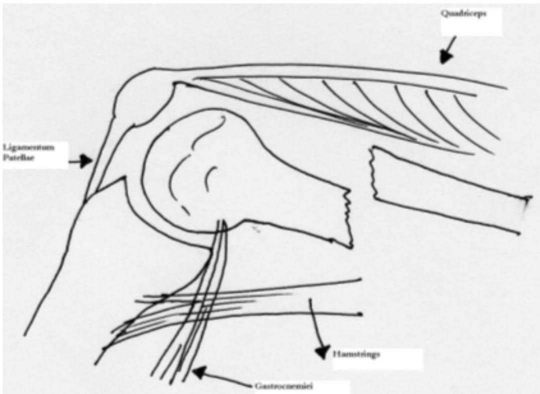


Figure 4: Deformity in supracondular facture femur

3 The Platform Robot

The robotic device chosen is in a platform with the top plate moving and the bottom plate fixed. Basic qualitative requirements set out are that: it is able to maintain reduction of fracture in both axial and rotational directions; it must have 6 DOFs and can be controlled in all directions; it must be controlled by the surgeon; it can have sensors to detect mal-alignment and correct it, if possible; it should be reasonably portable with small footprint to work in an operating theatre environment; and it should be reproducible in an industrial environment with low cost of production.

The initial design of the robot was done by Solidworks® (Solidworks Inc) and the motion analyzed was done by Cosmos™ software. The robot consists of two circular plates connected by six linear actuators in single ring configuration (Figure 5b). The top plate diameter is 350 mm and bottom plate in 500 mm and both are made of aluminum and 12 mm thick. The plates are connected by six linear actuators (LINAK™) which have a stroke length of 200mm and each can take a load up to 40kg. The maximum force generated by each actuator can be as much as 400 Newton. The actuators are connected to the top and bottom plates by ball and universal joints respectively. This gives the top plate three degrees of translation and three degrees of rotation. The movement range of the top plate (in standard configuration, Figure 5b) is shown in Table 1 and the physical parameters of the robot in Table 2. The actuators also have encoders attached to them to determine the position in space and how the actual trajectory of fracture reduction is followed, as shown in Figure 6. As the top plate moves the trajectory can be plotted in the workstation.

Figure 5: Two platform robots, a) double-ring configuration and b) standard configuration

Table 1: Range of the Robot's Movement

	Double Ring Configuration	Single Ring Straight Mount	**Single Ring Angular Mount**
Rotation X – α	± 10°	± 5°	**± 10°**
Rotation Y – β	± 25°	± 25°	**± 35°**
Rotation Z – γ	± 10°	± 5°	**± 10°**
Translation X	± 100 mm	± 50 mm	**± 100 mm**
Translation Y	± 200 mm	± 200 mm	**± 200 mm**
Translation Z	± 100 mm	± 50 mm	**± 100 mm**

4 Motion Control System

The robot is controlled by a Galil™ DMC-1680 motion control card which is interfaced to the PC and is graphically represented on the desktop by the Galil™ software which controls the actuators through two AMP-19540 amplifiers (Figure 7).

While the robot is in operation its actuators are controlled to follow the trajectories generated in the planning phase. The output motions are measured and compared to the commanded for the servo control purpose. Care was taken to limit the actual torque as each actuator has 400N force and a cut off mechanism to limit torque was instituted.

Table 2: Physical parameters of the robot

	Mass (Kg)	Dimensions (mm)	DOF	Joint Range
Top Plate (mobile plate)	3.0	Ø350 x 12	-	-
Base Plate (ground plate)	6.4	Ø500 x 12	-	-
Linear Actuator	1.5	Ø50 x 390 + 200	1	200 mm
Ball Joints	0.035	Ø20 x 34	3	± 15°
Universal Joints	0.093	Ø17 x 62	2	± 45°

Total mass = 19.2 Kg
Height when fully retracted = 457 mm (ground to top plate)
Height when fully extended = 660 mm (ground to top plate)

Figure 6: The built robot with hall-effect sensor for positional measurement

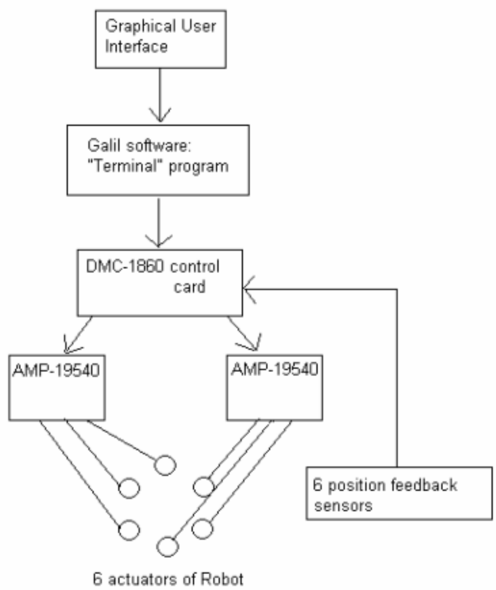


Figure 7: Galil motion control configuration

A separate interface to track the trajectory of a fracture reduction was done. Currently in the SolidWorks and Cosmos/Motion environment, the robot can be moved manually by the surgeon in a certain trajectory and the resultant motions of the actuators are imported into the motion control software. This in turn moves the actuators and the top plate in the defined trajectory (Figure 8).

Figure 9 presents an example of bone fractures realignment experiment. Given the displacement of the bones a surgeon did manual realignment on screen and the command position of one actuator was extracted as given in Figure 10 (the top curve). The final actual position of the actuator is given in Figure 10 (the second curve from the top). As the graph shows, the actual trajectory of the robot followed the predefined path specified by the surgeon well.

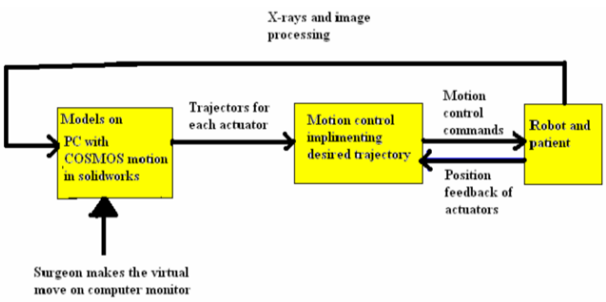
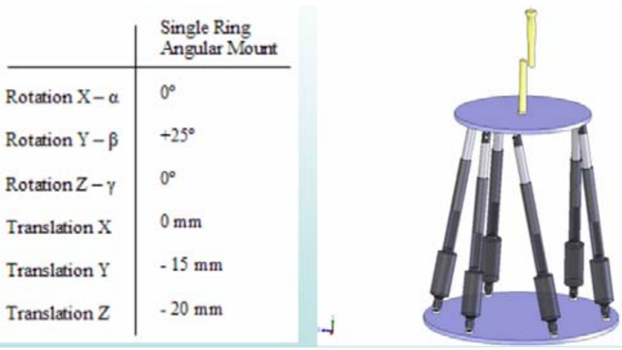


Figure 8: Closed-loop control of a linear actuator



	Single Ring Angular Mount
Rotation X – α	0°
Rotation Y – β	+25°
Rotation Z – γ	0°
Translation X	0 mm
Translation Y	- 15 mm
Translation Z	- 20 mm

Figure 9: Example of a bone fractures realignment

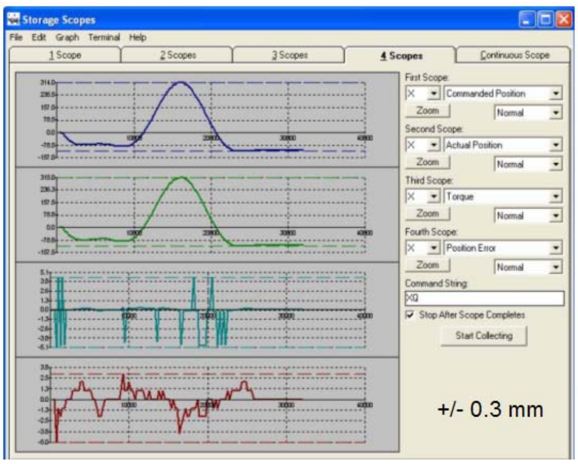


Figure 10: An actuator following the generated trajectory for example realignment in Figure 9

5 Reconstruction of 3D Bones

The construction of a 3D model in CAD environment is essential for the control system of the robot. For the creation of the 3D model two 2D x-ray images were given. After evaluating several different ways of common image processing, it was obvious, that a fully automatic program which reconstructs the image was not possible because of the restrictions in fluoroscopic images. The distinct automatic determination of layers is not possible, as fluoroscopic images provide bad contrast. Furthermore the soft tissue attachments make it hard to recognize and to distinguish the bone itself from nearby joints.

Our solution was interactive software called *"XRay2CAD Wizard"* we developed, which uses the eye of the surgeon and his experience. Figure 11 shows its GUI. As the way of looking at x-ray images is always the same, the information of important points can be stored as coordinates in a matrix. Another benefit of this technique is that irregularities can be easily recognised by the experienced surgeon. Accordingly the probability of errors is minimized.

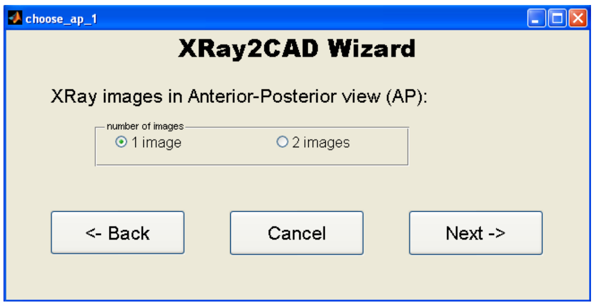
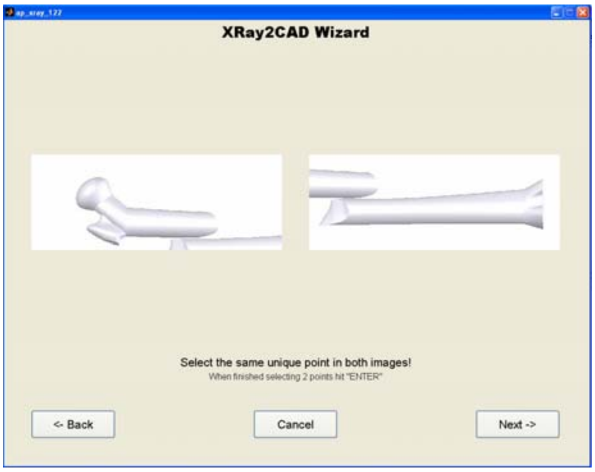


Figure 11: GUI for panorama creation

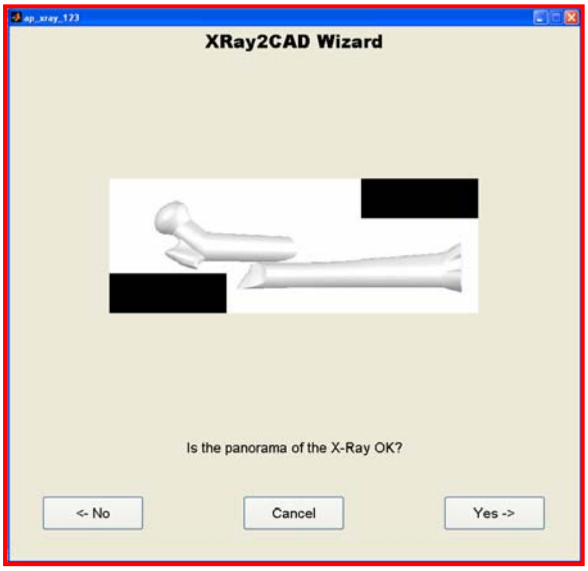
As platform for the image processing Matlab was chosen. It was the first choice because of the easy implementation of images as matrices and creation of Excel worksheets which can be later used as design tables in SolidWorks.

The first step of the software is to create a complete panorama of all the x-ray images. The size of the bones makes it sometimes impossible to fit the whole bone with its attached joints on one x-ray. The merging of the images is done by selecting the same unique point on each of the 2 corresponding x-ray images. The coordinates of the points create a displacement vector of the two images. After separating the second image in different matrices, the resulting matrices were merged with the first image so that a whole panorama was created. The more careful the unique points are selected the better the result will be. The resulting image will be also available for further processing. Figure 12 shows an example of this step.

The next step is to get the coordinates of the important points. They will be selected by the user of the *"XRay2CAD Wizard"*. These points are important for the dimensions of the bone, the details of the broken area and the relative position of the broken pieces. A total of 22 points have to be selected for both views (anterior-posterior and lateral). The information is written to a Microsoft Excel file which will be used in subsequent steps.



(a) Displacement vector creation



(b) Final panorama

Figure 12: The merging of two x-ray images

All the information which is necessary for the CAD model can be determined from the coordinates. The two x-ray images provide enough information for the 3 translational DOF and 2 rotational DOF (see Figures 13 and 14). They are computed by Excel formulas based on trigonometry. For the third rotational DOF (rotation about the axis of the bone) an x-ray of the unbroken bone is being looked at. It is compared with the broken pieces. The relative length between two points on each part is enough information to generate the missing DOF. A numerical search algorithm in Matlab finds the best fitting solution for the angle. The result of the third step is a rotation matrix including all 6 DOF, as given in Figure 15.

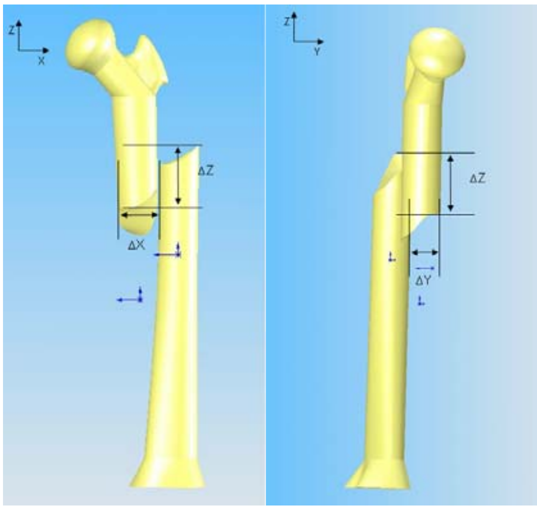


Figure 13: Three translational degrees of freedom

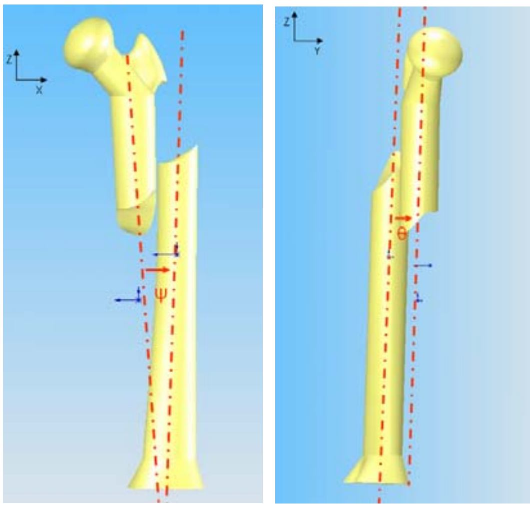


Figure 14: Two rotational degrees of freedom

Translation:

$$T=\begin{bmatrix}1 & 0 & 0 & \Delta x\\ 0 & 1 & 0 & \Delta y\\ 0 & 0 & 1 & \Delta z\\ 0 & 0 & 0 & 1\end{bmatrix}$$

Rotation: about z-axis:

$$x' = x\cos\varphi - y\sin\varphi$$
$$y' = x\sin\varphi + y\cos\varphi$$
$$z' = z$$

$$R_z=\begin{bmatrix}\cos\varphi & -\sin\varphi & 0 & 0\\ \sin\varphi & \cos\varphi & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\end{bmatrix}$$

about x-axis:

$$x' = x$$
$$y' = y\cos\theta - y\sin\theta$$
$$z' = y\sin\theta + z\cos\theta$$

$$R_x=\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & \cos\theta & -\sin\theta & 0\\ 0 & \sin\theta & \cos\theta & 0\\ 0 & 0 & 0 & 1\end{bmatrix}$$

about y-axis:

$$x' = x\cos\psi + z\sin\psi$$
$$y' = y$$
$$z' = -x\sin\psi + z\cos\psi$$

$$R_y=\begin{bmatrix}\cos\psi & 0 & \sin\psi & 0\\ 0 & 1 & 0 & 0\\ -\sin\psi & 0 & \cos\psi & 0\\ 0 & 0 & 0 & 1\end{bmatrix}$$

Resulting Matrix (rotation and translation): M=T*R.*R.*R.

Figure 15: Computing involved in the bone manipulation

The similarity of the bones is used in a parametric model of SolidWorks. The bone part attached to the hip as well as the part attached to the knee is separately created. Both pieces are put together in an assembly so they can be moved. The dimensions of the bones including the shapes of the broken area are available from the Excel worksheets. SolidWorks can create a 3D model and assembly from the information given by Matlab.

Automation is a very important task of software. To ensure the most comfortable way of handling the program a graphical user interface was developed which guides the user through all the steps. The automation of the whole process is being done by an ActiveX interface between Matlab and Microsoft Excel, which enables Matlab to access Microsoft Excel's classes and methods. Another convenient and applied way of speeding up data processing is macros written in VBA6 in Microsoft Excel and SolidWorks.

6 Conclusion

A surgeon-instructed, image-guided and robot-assisted system for long bone fractures reduction was proposed. The design of the system was specified in terms of mechanical, control and vision aspects. The robot in a platform was designed, built and simulated. The motion control was implemented via a Galil system. The x-ray images were processed and converted to a 3D model in CAD environment where the robot model and the bone model reside for planning.

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