

defined as a cube with 40 mm edge length and a volume of 64 cm³. Rotations of $\pm 20^\circ$ in all axes have to be achieved within this workspace. The installation space is defined as a cylinder tightly circumscribing the kinematics in their smallest configuration (e.g. struts fully retracted). Both parallel-kinematics-based robots have electromagnetic linear actuators and are designed to meet the same workspace specifications as the Epizactor. The Hexapod uses six struts of variable length between the base and the tool platform while the Hexaglide provides six base-fixed linear actuators and six passive struts of constant length. The simulations are based on inverse kinematic models of the three robots and are performed using software built in the Matlab/Simulink[®] environment.

Results

A cylinder enclosing the Hexapod has a minimal volume of 3941 cm³. This leads to a ratio of workspace and installation space of 1:62. The Hexaglide can be enclosed by a cylinder with a minimal volume of 4247 cm³ so the ratio of workspace and installation space can be computed to 1:66. A cylinder circumscribing the Epizactor has a volume of 1445 cm³. Compared with the required workspace this leads to a ratio of workspace and installation space of 1:23.

Conclusion

The three robotic devices have been designed to optimally meet the workspace specifications. For each kinematic approach, a prototype has been built, simulated, and tested during our projects so the comparison is permissible. Using kinematic simulations it could be shown that the Epizactor provides a ratio of workspace and installation space almost three times better compared to the Hexapod or the Hexaglide. Unlike articulated arm robots – often used for medical robots – providing large workspaces but also very high velocities, the Epizactor is designed to meet the exact specifications of endeffector velocity and workspace size. This leads to an inherent safe behaviour of a robot based on this kinematic approach. Furthermore the tool rotation around its z-axis, which is not limited by mechanical constraints, can be used to drive a milling tool. So an additional spindle drive can be omitted, which results in an even smaller installation space of the robot. The promising properties of the Epizactor lead to the decision to create a robot for orthopaedic surgery within our new CYCLOBOT project. This robot will be bone-mounted and can be used for bone milling during the implantation of artificial joints and other milling tasks. For bone mounting the robot has to be as small and lightweight as possible and should not occlude the surgeon's view of the situs. As Fig. 2 shows, the surgeon can literally see through the device and observe the situs during the milling task. However, the presented prototype does not yet meet all specifications concerning the size of the workspace and clinical deployment. The next steps within the CYCLOBOT project are the creation of a second, more advanced prototype and an appropriate control system. This prototype will meet the geometrical and dynamic specifications and allows an experimental use within the robotics laboratory simulating a surgery environment. Aim of this project is the scientific assessment of the robot's characteristics, elastic behaviour and accuracy. The Epizactor's kinematic concept easily allows the deployment of mechatronic devices with a considerable large workspace within the spatial limitations of the surgical environment.

Semi-automatic bone fracture reduction in surgical planning

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Keywords Surgical planning · Fracture reduction · Registration
Purpose

The surgical intervention of complex bone fractures has to be planned very carefully, especially for such a complex region as the pelvic ring.

The computer aided surgical planning is done before the actual surgery takes place and its main purpose is to gather more information about the dislocation of the bone fragments and to arrange the surgical implants to be inserted. With the help of finite element analysis even the biomechanical stability of the whole plan can be predicted.

To create such a plan the following steps are performed. First, the CT dataset of the patient is segmented [1], which enables us to treat the different bones and broken fragments separately. Next the surface of this volumetric dataset is determined [2] and presented in a 3D environment. Since the fragments may have moved during the fracture, it is essential to move and rotate them back to their original anatomic position. Without this reduction, no implants can be inserted, since the final locations of the fragments are unknown. Previous solutions to the fracture reduction problem included moving the fragments with the mouse, or a special 3D haptic device. The former is not intuitive to use since the mouse is only 2D, and the later is expensive and still requires learning.

Methods

In this paper we present a semi-automatic method for the fracture reduction problem. It is semi-automatic because the user has to select the healthy and the fractured bone fragments on order to proceed. Selecting a fractured fragment is done by simple clicking. The healthy bones can be loaded from a library or, in cases of single side fractures the intact bones are mirrored and translated.

The fracture reduction problem is basically a search for the three translational and three rotational parameters of each fragment to match the healthy bones. During our search we minimize a cost function consisting of two parts. The first part guides the fragments in the direction of the healthy bones and the second part prevents them from overlapping.

To speed up the computation of the first part a distance map [3] is used. This map is a 3D array containing the pre-computed distance to the healthy bone for every voxel. The distance map uses the same resolution as the original CT scans. In the calculation of the cost function the actual transformation is applied on the surface points of the fragments, and the corresponding values from the distance map are summed. The second part of the cost function can be computed faster on the volumetric data. Since the segmented volume is still available, we scan through each object voxel and transform it with the actual transform and store it in another volumetric array. If different objects share the same space, than this results a high penalty in the cost function.

To reduce the search space we included constraints on both the translational and rotational components: we permit only 5 cm movement and 20 degrees rotation. The function optimization method we used was an Evolutionary Algorithm from the OAT library [4] with a population size of 400 and lack of improvement served as stop condition.

Results

The described method was implemented in our preoperative surgical planning system. All used data originated from CT scans of real patients pelvic fractures. The smallest CT dataset contained 41, the largest 147 slices. The number of fragments varied between 3 and 8. The number of points on the 3D surface was between 20 and 50 thousand.

Our clinical expert used the mouse to move and rotate the fragments to their original positions and we considered this as the best solution. We also measured the time he needed to complete this task, which was 6–20 min depending on the number of fragments and how complicated the fracture was.

The same patient data were also aligned by the described method. The running time was between 30 and 60 s. Compared to the manual solution the average difference of the translational and rotational components were 3.2 mm and 4.8 degrees respectively.

Figure 1 shows a pelvic ring fracture with four major and three minor fragments before (left) and after (right) the fracture reduction.

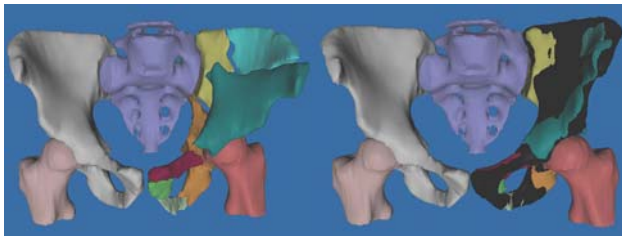


Fig. 1 A pelvic ring fracture with four major and three minor fragments before (left) and after (right) the fracture reduction. The mirrored and translated healthy side is shown black

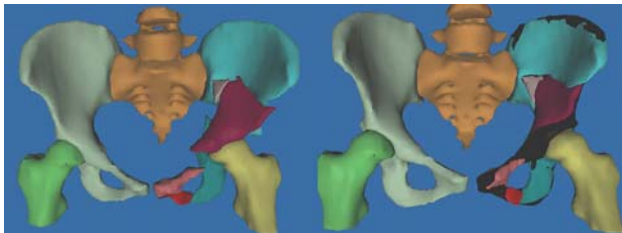


Fig. 2 A pelvic ring fracture with three major and three minor fragments before (left) and after (right) the fracture reduction. The mirrored and translated healthy side is shown

Since the right hand side of the pelvis is intact, this was mirrored and translated to the centroid of the fragments and is shown black on the right. The other colors are simply for better distinction. Figure 2 gives another example of the alignment of the fragments.

Conclusion

Using this method the fragment repositioning task can be done faster than with the mouse in particular for complicated cases; however human verification of the result is still required. The surgeon can spend more time on other parts of the preoperative planning, like plate and screw insertion or analysis of the biomechanical tests

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Automatic distraction osteogenesis with a bone mounted hexapod robot

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Keywords Fixator · Bone mounted robot · Osteogenesis

Purpose

External fixation is a well established technique to stabilize bone fragments in fracture fixation and distraction osteogenesis. Fracture treatment primarily requires immobilization and anatomical reduction of the fracture gap, while distraction osteogenesis utilizes exact fixator movements to gradually form new tissue. The gradual distraction stimulates the body's self healing capacities to form new bone and has been proposed for limb-lengthening and treatment of deformities already 100 years ago. The hexapod external fixator is based upon parallel kinematics well-known from high-precision robotics. This allows for fracture movements in all six degrees of freedom without losing stability of fixation. In current clinical routine the fixator movements are effected manually by the patient several times a day over the course of healing. For the robotic hexapod external fixator motor-driven actuation supersedes the manual fixator movements while in-vivo load measurements of the fracture site make x-ray free control of the osteogenesis possible.

Methods

The robotic hexapod external fixator implements the Stewart Platform kinematics which allows for movements in six degrees of freedom. Six linear actuators (distractors) are fixed on two rings with non-blocking ball joints. A motor-driven actuator with an embedded force sensor was developed to replace the manual elements of the hexapod external fixator. It contains a dc-motor (13 mm diameter) with planetary gear head and a magnetic encoder. Four strain gauges on the actuator detect the longitudinal force. An embedded Micro-controller (Cypress PSoC) controls the speed and position of the motor; it maintains the current position of the actuator in non-volatile memory and also performs the force measurements. The actuator was investigated with respect to speed and accuracy of positioning. One of the ball joints was fixed and the second mounted movable. To allow for measurements with variable distractor loads a cable with interchangeable weights is routed over a pulley and connected to the movable joint. Speed measurements were conducted with a constant supply voltage of 6 V. The speed was determined by evaluation of the magnetic encoder. The robotic hexapod external fixator with six

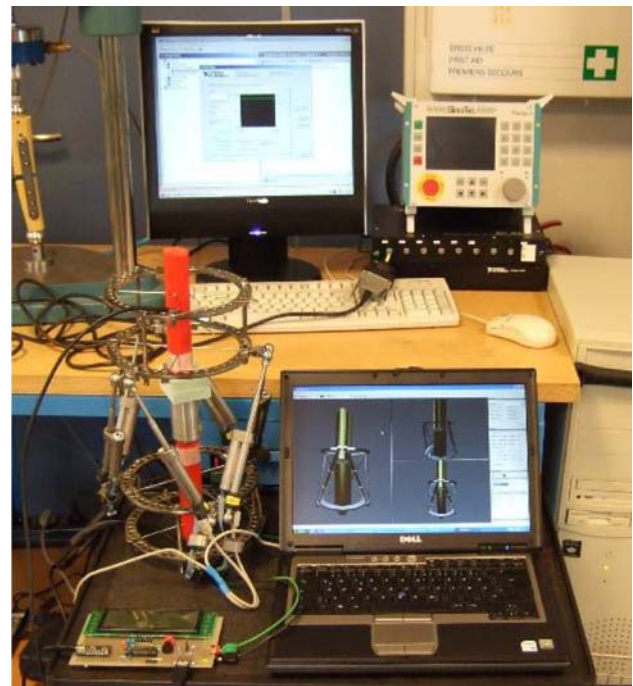


Fig. 1 Test setup for the robotic fixator