Optimizing Joint Placement and Motion Schedule for 2-DOF Computer-Assisted Distraction Osteogenesis

Robert OBERREUTER, Ryan LUCKING, Kenji SHIMADA
Carnegie Mellon University, Pittsburgh, PA

Abstract. Distraction osteogenesis is a surgical procedure used to correct severe bone deformities. Current practice involves planning the deformity correction using parameters measured from radiographs and the installation of complex fixators such as the Taylor spatial frame. A computer-integrated surgery system has been proposed that uses a novel two-degree-of-freedom fixator to correct complex bone deformities. The proposed fixator is designed such that the two joints can be positioned and oriented arbitrarily to achieve proper alignment of the bone fragments while following a desired trajectory. This paper describes the fixator configuration methods and trajectory planning procedures used to prove the feasibility of such a device. It is shown that this device is applicable for a variety of deformity types and realignment trajectories.

Keywords. Orthopedics, distraction osteogenesis, external fixation, computer-aided surgery

Introduction

Severe bone deformities are commonly treated with a procedure called distraction osteogenesis. First, an osteotomy is performed followed by the attachment of an external fixator to the two bone fragments. Post-operatively, the fixator is used to gradually displace the fragments with respect to one another to simultaneously realign the bone fragments and generate new bone tissue between the fragments.

Standard practice for distraction osteogenesis requires determining deformity parameters manually using radiographs then using a parallel-ring fixator such as the Taylor spatial frame (TSF) to carry out the deformity correction [1]. The TSF has six adjustable struts and is capable of moving a bone fragment to an arbitrary position and orientation [2]. The drawbacks of the current methodology are that complex deformity parameters need to be determined manually, that the TSF is large and bulky, and that a patient need to adjust six struts.

A computer-integrated surgery (CIS) system for distraction osteogenesis has been proposed to address these shortcomings. The system first creates a 3-D image of the bone based on two orthogonal radiographs using a recently developed method [3]. Using the patient-specific 3-D model the deformity parameters can be determined accurately. The deformity is then corrected with a novel two-degree-of-freedom (DOF) fixator device shown in Figure 1. The proposed fixator is a hyper-redundant kinematic chain containing one rotational and one prismatic joint. The device operates on the principle that arbitrary positioning can be reduced to a single rotation and single translation with carefully chosen axes. Small chain links are placed between the rotational joint and the translational joint, as well as between the joints and two ends of the fixator. This fixator design enables a surgeon to place the two joints to the position and orientation specified by the CIS system. The surgeon can then make the chain links stiff by tightening screws on the chain links.

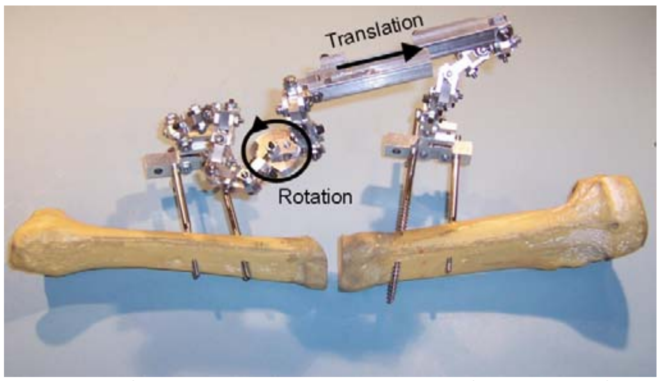


Figure 1. Prototype 2-DOF fixator device. Kinematic chain is shown frozen allowing for proper alignment of the rotational and translational axes.

1. Planning Fixator Configuration and Motion Schedule

The inputs to the system are the initial geometry of the deformed bone, the target geometry, and a desired trajectory of realignment. For this study a tibia model with a 38° angulation and 10° internal-rotation deformity was used. It was assumed that a lengthening of 5 cm was desired. This severe deformity was chosen as the test case to explore the limitations of the device.

Using the bone model, descriptive coordinate systems based on standard orthopedic practices can be derived. Coordinate systems at the proximal and distal ends of the tibia can be created using the orthogonal vectors found from applying the cross product of joint orientation lines and by using the center of the joint as the origin. Other target frames can be determined from the proper anatomic-axis alignment, the desired lengthening, and an osteotomy plane decided upon by the surgeon. After these parameters have been decided upon, the correction can be completely described by the relative motion of two frames.

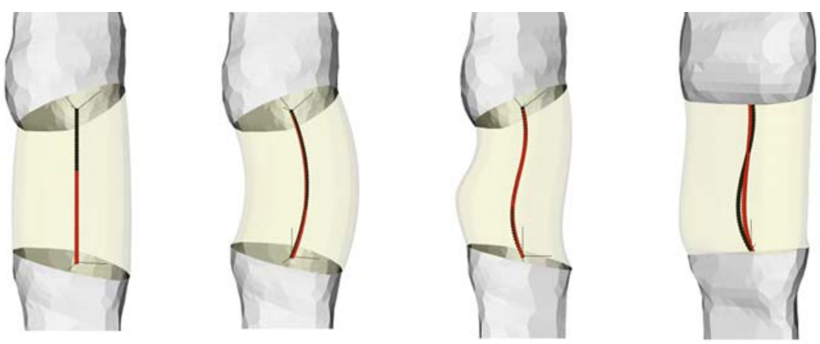
The configuration of the fixator can be described by orientation of the rotation and translation axes, and the position of the rotation joint. The total angle of rotation and the rotation axis can be found by relating the initial geometry to the final geometry through the transformation matrices of the descriptive coordinate systems. The position of the rotation joint will induce secondary translation during rotation. This secondary translation is addressed by the prismatic joint orientation and final length. The position of the rotation joint affects the achievable workspace of the fixator and was optimized for a given deformity and trajectory. Movement schedule functions $\theta(t)$ and $l(t)$ were modeled using cubic polynomials and optimized to match the given trajectory.

2. Results

Figure 2 shows the results of the system planning for the correction of the tibia with the angulation and internal-rotation deformity. Linear, quadratic, and cubic desired trajectories were tested. Two cubic trajectories were defined to distinguish whether the trajectory lied in a single plane or was three dimensional (in-plane versus out-of-plane). The computed trajectories matched up very well in the linear, quadratic, and in-plane cubic cases. Significant error was only found in the out-of-plane cubic case when the trajectory deviated out of the plane normal to the rotation axis, a situation that is quite rare in the practice of bone-deformity correction with distraction osteogenesis.

3. Discussion

Given the initial and final bone geometries, the software was successful in determining a configuration and movement schedule for the proposed fixator. The concept of using a 2-DOF fixator was proven to be viable for complex deformities and a variety of realignment trajectories. Future research includes developing an automated process for identifying deformity parameters and implementing multi-stage correction.



(a) linear target trajectory (b) quadratic target trajectory (c) cubic in-plane target trajectory (d) cubic out-of-plane target trajectory

Figure 2. Generated trajectories (red) compared to target trajectories (black) for a 38° angulation, 10° internal rotation deformity of the tibia.

References

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