Computer-Assisted Correction of Bone Deformities Using a 6-DOF Parallel Spatial Mechanism

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Abstract. The Ilizarov method is used to correct bone deformities by using an adjustable frame to simultaneously perform alignment and distraction of an open-wedge osteotomy. We have adapted the idea of fixation-based surgery, which requires computer-assisted planning and guidance, to the Ilizarov method with the Taylor frame.
This work incorporates the kinematics of the Taylor frame (a Stewart platform) into the planning and application phases of surgery. The method has been validated in laboratory studies. The study shows that the method requires almost no intraoperative X-ray exposure and that complex corrections can easily be achieved.

1 Introduction

In previous work [2] we introduced the idea of fixation-based surgery, using a fixed plate to distract, align, and fixate bone fragments during corrective wrist surgery. The Ilizarov method also requires distraction, alignment, and fixation but with an adjustable external-fixation frame (rather than with a simple plate). The fundamental concept here is similar to assembly of manufactured components: fixation holes are drilled in the bone fragments, the frame is attached to the bone, the bone is cut, and the frame is adjusted to move the fragments into a new alignment.

Here, we show that fixation-based surgery can be used to improve the Ilizarov method when using a six-degree-of-freedom parallel mechanism, the Taylor spatial frame. We planned a corrective procedure, used the inverse of the plan to compute the kinematics of the Taylor frame, and used computer guidance to help a surgeon apply the frame to a deformed bone. This is a new way of performing complex corrections of deformities of the extremities.

1.1 The Ilizarov Method

The Ilizarov method of osteogenesis by distraction and fixation, developed in 1951 by Russian orthopædic surgeon Gavril Abramovich Ilizarov, is used to correct rotational and translation deformities in the three axes of motion. The Ilizarov method is done by performing osteotomies on the healthy portions of the deformed bone and distracting at a regulated rate to promote bone growth [6]. The method eliminates the need to destroy tissue, insert permanent artificial screws or metals, inject compounds or immobilize bones for months in a cast, and has been found to be highly successful in the treatment of angular deformities, malunions, non-unions, pseudoarthroses, bone infections, open fractures, post-traumatic osteomyelitis, limb lengthening, bone gaps, poliomyelitis, club

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foot, congenital and acquired disorders of the limbs, dwarfism, skeletal defects, stump elongation and joint contractions [6,1,4,12,9,8].

Preoperative planning is done by using X-ray images to measure angular and translational discrepancies in the anterior-posterior and medio-lateral views, and clinical examination to measure rotational and translational deformity in the axial direction. These measurements are used to determine the initial and final shapes of a distraction frame (the Taylor frame is one of many frames used in the method).

Intraoperatively, the surgeon applies the frame to the patient with the aid of fluoroscopic images and performs a low-energy cortical osteotomy. The patients are usually discharged after a few days and scheduled for outpatient visits for both physical therapy and a monitoring of the healing process. The frame is used to rotate and translate the bones at up to 1mm per day. The distraction of the bones induces the growth of new cortical bone. With the use of additional X-ray images, the surgeon can change the configuration of the Ilizarov frame to ensure adequate correction of the problem.

1.2 The Taylor Spatial Frame

The Taylor Spatial Frame, invented by Dr. John Charles Taylor, is an external orthopedic fixator device used to implement the Ilizarov method. The device is kinematically equivalent to a Stewart platform [10,3], consisting of two circular bases or rings, six telescopic linkage rods (also called struts), and twelve universal joints that connect the struts to the rings [11]. The six measurements used to characterize deformities are related to the displacements on the struts by inverse kinematics.

Preoperatively, a surgeon determines the desired correction and specifies the *neutral* shape of the frame, which is the intended shape when the distraction schedule is complete. A computer program then calculates the strut lengths in the initial and final desired shapes. Intraoperatively, as with other Ilizarov frames, the Taylor frame is attached to the deformed bone with wires, full pins, or half pins. Postoperatively, after the correction schedule has been completed, any residual deformity can be corrected. This is done by developing a new plan that will change the Taylor frame from a *neutral* shape to a final shape which is similar to the initial shape of the first correction. This final shape is dependent on the residual deformity present. A new correction schedule can also be calculated. The Taylor frame, in its initial and neutral shapes, can be seen after application to a plastic bone model in Figure 2.

1.3 The Problem and the Approach

Error in preoperative planning is the most important factor in poor results from use of the Ilizarov method [9]. A secondary source of error is “mis-application” of the frame, which is the failure to place the frame in the intended position and orientation.

We seek to improve the accuracy of Ilizarov’s method by (a) planning the correction from a patient-specific CT scan, and (b) using image-guidance technology to apply the frame to a patient. We use many of the same ideas from our fixation-based method of distal radius osteotomy: both that work and the Ilizarov method employ fixation as an essential part of distraction and alignment of bone fragments [2].

2 Materials and Methods

Our laboratory study compared results of conventional application of the Taylor frame with computer-assisted planning and application. This section describes the surgical techniques and the analytical methods used in the study.

2.1 Conventional Technique for the Taylor Frame

The surgeon first planned the procedure by determining the nature of the deformity and the specific mechanical parameters of the Taylor frame. The rotational parameters were angles θ, ϕ and δ[1]. The parameter θ was the lateral angulation, taken from an AP view; ϕ was the angulation, taken from a lateral view; and δ was the axial rotation, usually determined by clinical examination.

The three translational parameters were determined similarly. The surgeon then determined the mechanical parameters, which were the size of the moving ring and the base ring, the *neutral* shape of the frame, and the XYZ position of the frame with respect to the osteotomy. The neutral shape was a symmetric configuration in which all struts have the same length, e.g., 145mm.

These parameters combined to determine the initial and neutral lengths of each strut, from which a daily schedule of strut lengths could be calculated. The calculations were performed by a program that is supplied by the manufacturer of the Taylor frame. These calculations determined the coordinates of each ring in the coordinate frame of the deformity (at the osteotomy site). One ring was the base ring, and had a constant pose that was determined from the XYZ position of the frame with respect to the osteotomy. The neutral pose of the mobile ring was initially a simple translation from the pose of the base ring, e.g., if a neutral strut length of 145mm is chosen then the height of the frame was found by simple trigonometry.

To find the initial strut lengths, a rotation matrix R and a translation vector $\boldsymbol{t}$ were calculated from the rotational and translational parameters. The mobile ring was rotated about the origin of the anatomical coordinate system and translated to its initial position. If the point where the i^{th} strut inserts into the base ring is $\boldsymbol{S}^b$ and the point where the i^{th} strut inserts into the mobile ring in the neutral shape is $\boldsymbol{S}_n^m$ then the point where the i^{th} strut inserts into the mobile ring in the initial shape is

$$\boldsymbol{S}_i^m = R\boldsymbol{S}_n^m + \boldsymbol{t}$$

and the initial length of the i^{th} strut is

$$L_i = \|\boldsymbol{S}_i^m - \boldsymbol{S}^b\|$$

Finally, a daily schedule of strut lengths was calculated. The maximum absolute strut change, in millimeters, is the number of days for the frame to be changed from its initial shape to its neutral shape, because the bone callus can be distracted at a maximum rate of 1mm per day. The lengths of each strut could thus be determined by linear interpolation.

[1] These are similar to, but not identical with, Cartesian or Grood-Suntay angular parameters [5]. The difference is that, for the Taylor frame, the angles are coupled because they are specified independently from the X-ray images rather than consecutively about axes.

We have shown[2] that rotation matrix can be reduced to

$$R = \begin{bmatrix} ec - bf & d & a \\ dc - af & e & b \\ db - ae & f & c \end{bmatrix} \tag{1}$$

where

$$a = c \cdot \tan(\theta) \qquad c = \sqrt{1/\left(1 + \frac{1}{\tan^2\theta} + \frac{1}{\tan^2\phi}\right)}$$

$$b = c \cdot \tan(\phi) \qquad e = \sqrt{\frac{c^2\eta^2}{c^2(1+\eta^2) + a^2 + 2ab\eta + b^2|eta^2}}$$

$$\eta = \tan(\pi/2 + \delta) \qquad f = \frac{-1}{c}e(\frac{a}{\eta} + b)$$

$$d = e/\eta$$

2.2 Computer-Assisted Technique for the Taylor Frame

Our surgical technique changed the conventional technique in two ways. First, we planned both the correction and the fixation preoperatively, with a computerized planning system. To mimic the intraoperative phase, we used computer guidance to implant the fixation pins in the desired locations and to guide the osteotomy.
The preoperative planning stage can be conducted in seven steps:

1. Develop a surface model of the deformed bone from a CT scan;
2. Determine the anatomical frame of reference (usually distal to the deformity);
3. Perform "virtual surgery" by cutting the deformed model and moving one fragment into a corrected position and orientation;
4. Position a model of the fixation pins, for a *neutral* Taylor frame shape, through the fragments;
5. Calculate the rotational and translational components of the correction;
6. Calculate the *initial* Taylor frame shape;
7. Calculate the *initial* positions of the fixation pins.

Figure 1 shows a CT-derived model of the deformed femur and a plan.

We used homogeneous coordinates to describe all spatial motion. A transformation from frame j to frame k was represented as

$${}^kT^j = \begin{bmatrix} {}^kR^j & \boldsymbol{t}^j \\ \mathbf{0}^T & 1 \end{bmatrix} \tag{2}$$

Using this notation, the planned correction in CT coordinates was $M^p = {}^cT^p$ and the location of the anatomical coordinate frame in CT coordinates was ${}^cT^a$. Thus, the plan in anatomical coordinates was

$$P^a = {}^aT^c \cdot (M^p)^{-1} \cdot {}^cT^a \tag{3}$$

[2] Contact the Corresponding Author for the mathematical proofs.

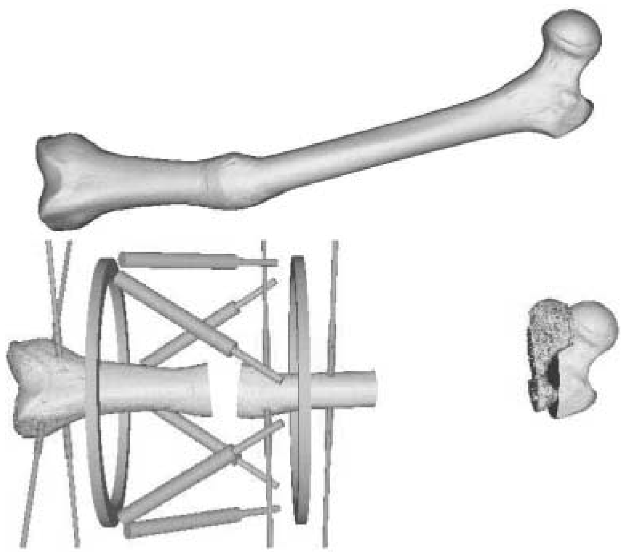

Fig. 1. A model of the deformed femur and a plan. The deformed femur has been cut, with the proximal fragment aligned to the model of the normal femur (shown as a green mesh) and lengthened by 25mm. The long cylinders indicate the planned placement of the fixation half-pins for the frame in its neutral shape (all struts at 145mm length).

The rotation matrix of this transformation was used directly to determine the positions of the initial struts on the mobile ring[3]. The matrix could also be decomposed to find the parameter angles θ, ϕ and δ as

$$\begin{array}{rl} \theta = & \tan^{-1}(a/c) = \tan^{-1}(R_{13}/R_{33}) \\ \phi = & \tan^{-1}(b/c) = \tan^{-1}(R_{23}/R_{33}) \\ \delta = & \tan^{-1}(e/d) - \pi/2 = \tan^{-1}(R_{22}/R_{12}) - \pi/2 \end{array} \quad (4)$$

so that the manufacturer's programs could be used to determine the daily schedule of strut lengths.

2.3 A Laboratory Study

Fourteen identical polyurethane-foam models of a single deformed femur (model #1164, Pacific Research Laboratories, Bellingham, WA) and one normal femur (model #1120) were used for the study. The normal femur was scanned by CT to represent the template for correction. Seven corrections were performed using the traditional procedure using fluoroscopy and seven using the computer planning and navigation system.

In each of the procedures, a fresh deformed femur was instrumented with two "target" plates containing infrared emitting diode (IRED) markers, one attached distal bone fragment and the other to the femoral shaft. The bone surface was registered to the base

[3] This was the planned correction, so the transformation of the mobile ring is actually the inverse of the planned correction.

target by a robust surface-point registration algorithm [7] so that the location of the anatomical coordinate system could be determined.

The locations of the two markers were captured before and after the procedure and used to analyze the overall correction established. Representing the initial poses of the base and mobile targets in the tracker frame as ${}^{b}T_0^t$ and ${}^{m}T_0^t$, the final poses as ${}^{b}T_1^t$ and ${}^{m}T_1^t$, and the registration as ${}^{c}T^b$, the relative motion of the mobile target in anatomical coordinates was calculated as

$$M^a = {}^aT^b \cdot {}^bT_0^t \cdot {}^tT_0^m \cdot {}^mT_1^t \cdot {}^tT_1^b \cdot {}^bT^c \cdot {}^cT^a \tag{5}$$

and so the residual error, which was the difference between the planned motion of Equation 3 and the actual motion of Equation 5, was

$$E^a = (P^a)^{-1} \cdot M^a \tag{6}$$

The errors were extracted from the matrix as the rotational and translational values used in determining the shape of the Taylor frame. The mean, standard deviation, and range were computed in Matlab (The Mathworks, Natick, MA). For accuracy, the mean translations and rotations were analyzed using Student's t-test. For repeatability, standard deviations were analyzed using the two-sample F-test.

3 Laboratory Results

One of us (DPB), a practising orthopædic surgeon trained in the Ilizarov method, measured the deformed femur and planned a correction. As Table 1 shows, this differs substantially from the CT-based plan.

Table 1. Plans from traditional examination and CT-based computer-assisted technique.

Source	Angles (deg)			Translations (mm)		
	x	y	z	θ	ϕ	δ
Traditional	20	10	0	0	0	25
Computer-Assisted	13.2	7.5	1.1	7.0	9.3	26.5

Figure 2 shows a deformed femur during one test run of the laboratory study, in which four pins and the osteotomy were performed with computer assistance. The visual agreement of the plan and the achieved result is excellent.

The residual error matrix of Equation 6 was decomposed into its six independent components for analysis. Table 2 gives the angular and translational residuals for fluoroscopic guidance. Table 3 gives the angular and translational residuals for computer-assisted guidance. For both techniques, the mean and standard deviations of the residuals is shown.

Statistical analysis shows that there is a significant difference in the individual angular residuals for θ (*p*<*0.012*), ϕ (*p*<*0.001*) and δ (*p*<*0.0001*). There is no significant

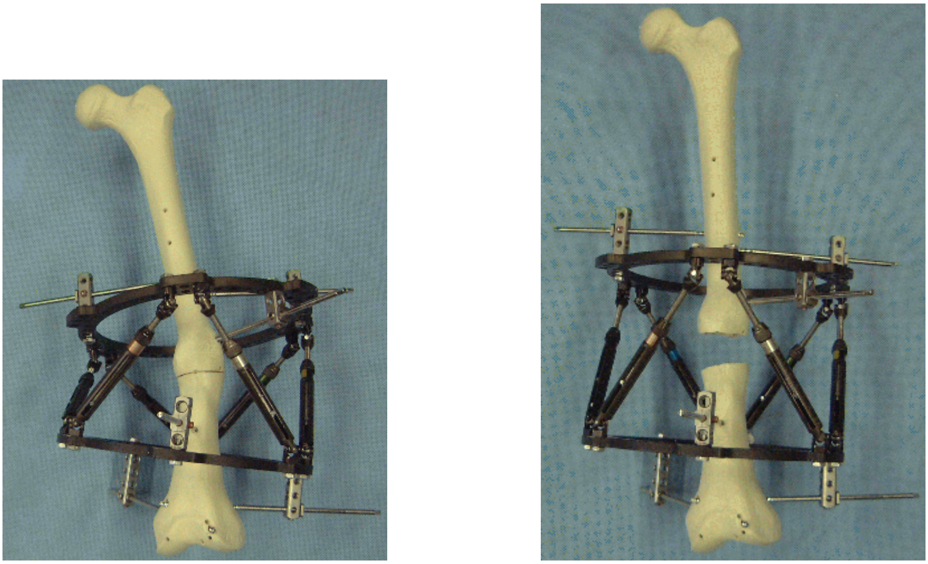

Fig. 2. The plastic model of a deformed femur from a trial using computer-assisted guidance. The Taylor frame is in the initial shape on the left and in the neutral shapes on the right.

difference between the individual or total translational residuals ($p<0.765$). Using the f-test for repeatability shows that the repeatability is nearly significant for translational corrections ($p=0.0975$) and not significant for angular corrections ($p=0.661$).

It is apparent that much of the difference between the residuals is in the first run using fluoroscopic guidance. If this run is discarded, the results are not statistically distinguishable.

4 Discussion

We have developed a technique for planning and performing the Ilizarov method with computer assistance. Our technique allows a surgeon to plan the 3D correction from a patient-specific CT scan, automatically calculate the kinematics of the Taylor frame to find both a distraction schedule and the planned location of fixation pins, and to use computer guidance to apply the frame intraoperatively to a patient. In a laboratory study, the difference between a traditionally derived plan and the 3D plan was substantial: in use, the patient would have needed an extra week of distraction therapy to correct for this difference.

In a test that compared fluoroscopic guidance with computer-assisted guidance, the computer-assisted technique was significantly better than the traditional technique. Both techniques had low residuals, but fluoroscopic guidance produced somewhat greater variances (less repeatable outcomes). Much of the difference is due to a single poor surgery, in which an overall angular error of about 6° produced large (25mm) translational errors because the kinematics of the Taylor frame couples rotations and translations intimately.

Table 2. Residual errors for corrections performed with traditional technique.

Run	Angular Differences (deg)				Translational Differences (mm)			
	θ	ϕ	δ	ψ_{total}	x	y	z	d_{total}
1	-3.6	-4.3	-1.7	5.9	-1.7	4.8	23.9	24.4
2	-1.2	1.1	-0.9	1.9	-2.7	-2.1	-4.0	5.3
3	-0.8	-1.2	0.4	1.5	-0.2	1.5	-0.4	1.6
4	-1.1	-2.1	-0.9	2.6	-4.8	2.7	0.1	5.5
5	-0.7	-2.9	-1.3	3.3	-0.3	2.1	1.2	2.4
6	0.3	-0.3	0.2	0.5	-1.6	1.7	-0.2	2.3
7	-1.3	-2.1	-1.1	2.7	-1.8	0.8	-1.5	2.5
Mean	-1.2	-1.7	-0.8	2.6	-1.9	1.6	2.7	6.3
σ	1.2	1.8	0.8	1.7	1.6	2.1	9.5	8.1

Table 3. Residual errors for corrections performed with computer-assisted technique.

Run	Angular Residuals (deg)				Translational Residuals (mm)			
	θ	ϕ	δ	ψ_{total}	x	y	z	d_{total}
1	1.4	2.2	1.4	3.0	-1.5	1.2	-6.1	6.4
2	1.7	3.1	1.1	3.7	-3.5	0.8	-7.8	8.6
3	0.9	1.6	1.4	2.3	-1.7	2.2	-3.6	4.6
4	-1.2	0.6	1.5	2.1	-3.3	2.3	-0.0	4.0
5	2.7	3.2	0.5	4.2	-3.0	-0.2	-4.2	5.2
6	0.9	3.5	1.4	3.9	-0.0	-2.5	-1.5	2.9
7	1.9	2.7	0.7	3.4	-2.3	-2.8	-4.6	5.9
Mean	1.2	2.4	1.1	3.2	-2.2	0.2	-4.0	5.4
σ	1.2	1.0	0.4	0.8	1.2	2.1	2.6	1.8

This study is limited by the relatively small number of runs (seven): many more samples are needed to eliminate the likelihood of Type II errors. The planning process was carried out under ideal conditions, with no soft-tissue obstacles such as nerves or blood vessels to complicate the process. The fluoroscopic guidance was extremely easy, also because of the very clean X-ray images available from phantoms.

Computer technology appears promising for reducing planning errors, which are a prominent concern in traditional technique [9]. Computer-assisted guidance appears to be significantly superior to fluoroscopic guidance, and is certainly no worse than traditional technique even if the one poor run is discarded. We are planning to conduct an approved clinical trial of our new technique for the Ilizarov method to study the outcomes for patients with complex bone deformities.

Acknowledgments

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