Computer–Assisted Deformity Correction Using the Ilizarov Method

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Abstract. The Taylor spatial frame is a fixation device used to implement the Ilizarov method of bone deformity correction to gradually distract an osteotomized bone at regular intervals, according to a prescribed schedule. We improve the accuracy of Ilizarov's method of osteogenesis by preoperatively planning the correction, intraoperatively measuring the location of the frame relative to the patient, and computing the final shape of the frame. In four of five tibial phantom experiments, we were able to achieve correction errors of less than 2 degrees of total rotation. We also demonstrate how registration uncertainty can be propagated through the planned transformation to visualize the range of possible correction outcomes. Our method is an improvement over an existing computer–assisted technique (Iyun *et al.* [3]) in that the surgeon has the same flexibility as in the conventional technique when fixating the frame to the patient.

1 Introduction

Rotational and translational deformities in the long bones are commonly corrected using a method of osteogenesis developed by Russian orthopaedic surgeon Gavril Ilizarov. Ilizarov's method is based on the biological principle of inducing new bone growth by gradually distracting a fracture at regular intervals. More specifically, the method is achieved by performing a corticotomy on the deformed bone, fixating the distressed bone with a mechanical fixator, and distracting the bone according to a set schedule of corrections. This technique has been successfully applied to treating malunions, nonunions, bone defects, limb elongation, fractures, and angular deformities, to name a few (Feldman *et al.* [2]).

Conventional surgical technique for the Ilizarov fixator is plagued by two sources of error: (1) preoperatively planning the required correction requires the precise measurement of 13 parameters from anteroposterior and lateral radiographs, and (2) angular and translational errors may be present once the frame is mounted to the patient.

1.1 The Taylor Spatial Frame

The Taylor spatial frame (Smith & Nephew, Memphis, TN) is an external fixator that combines gradual distraction principles of the Ilizarov method with deformity analysis provided by a computer program. The frame consists of six telescopic rods (called

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struts) that connect two circular bases (or *rings*), in a symmetric configuration of a Stewart–Gough platform [7]. By simply adjusting strut lengths, one ring moves with respect to the other and can be positioned to mimic any deformity (Taylor and Paley [9]).

Preoperatively, the surgeon determines the nature of the deformity, the desired correction, and the final (or *neutral*) height of the frame. Six specific strut lengths are calculated by a computer program using the initial and desired final frame configurations. Intraoperatively, the frame is attached to the bone by placing each ring substantially perpendicular to the bone, lengthening the six struts according to the preoperative plan, and fixating the frame with a combination of Kirschner wires, Steinman pins, and Rancho cubes (for attaching the wires or pins to the rings). The correction schedule is prescribed postoperatively by the surgeon. Once the correction schedule is complete and the frame is in its neutral position, any residual deformity is corrected by applying a secondary correction schedule; this residual correction phase is usually required (Taylor and Paley [9]).

1.2 Related Work

Early work by Kochs [4] attempted to reduce complications due to incorrect preoperative planning and inaccurate application of the frame by simulating the planned correction. Optimal joint positions and ring locations were obtained by simulation on images acquired from hand–tracing radiographs and scanning these images. Postoperatively, a radiograph was compared to the preoperative plan to determine the necessary residual corrections. Lin *et al.* [5] proposed a preoperative planning system for the Ilizarov method by (1) creating a bone template using an ultrasonic digitizer, (2) manually characterizing the deformity from radiographs and patient examination, (3) determining the weight–bearing axis, (4) performing virtual osteotomies on the computer, (5) aligning the bone fragments in the preoperative plan, (6) constructing the frame based on a physical examination of the patient, and (7) assembling the frame using a life–size diagram of the fixator assembly output by the computer.

More recently, Iyun *et al.* [3] proposed a method to apply the inverse kinematics of the Taylor spatial frame to calculate the initial position of the frame and fixation pins, the strut lengths, and the daily schedule of corrections. This research combined preoperative planning of the strut lengths with intraoperative guidance of the placement of the Kirschner wires and Steinman pins. Their methodology has two impractical assumptions. The first and most significant assumption was that the frame is always mounted using rigid pins or wires, which is not the case when a ring is mounted close to a joint line (where weaker bone can result in deviations from the rigid–fixation assumption). The second assumption was that the location and direction of the fixation pins could be determined during the planning phase. In practice, the configuration of the Rancho cubes, pins, and wires are best chosen intraoperatively because of anatomical constraints that may not be apparent preoperatively. The laboratory study was further limited by a learning effect present in the results; once the surgeon mounted the first frame in the conventional manner, subsequent frames were mounted without error.

1.3 Our Approach

Rajacich *et al.* [6] observed that a single point of failure in applying the Ilizarov method is planning the procedure. In the case of the Taylor spatial frame, 13 frame parameters must be measured from the patient and radiographs. Since the Taylor frame is tightly coupled (Stewart [7]), errors in any one parameter propagate through the entire preoperative plan. A second source of error is the misapplication of the frame such that translational and angular problems are introduced during surgery.

We aim to improve the efficacy of the Ilizarov method by (1) eliminating the need to measure parameters preoperatively, (2) allowing the surgeon complete flexibility in frame placement and configuration, and (3) improving the accuracy of the correction. Our method relies on the idea that it is not necessary for the frame to end in a neutral, or highly symmetric, configuration. The surgeon can simply mount the frame on the patient and, based on the actual position of the frame relative to the patient, we can compute the strut lengths and required schedule of adjustments to achieve the desired correction.

2 Methodology

In this section, we describe the conventional surgical technique for applying Ilizarov's method using the Taylor spatial frame as well as the proposed computer–assisted technique.

2.1 Traditional Surgical Technique

In the conventional technique, the surgeon measures the deformity, plans the necessary correction, and specifies the 13 mechanical parameters of the Taylor spatial frame. The three rotational parameters are measured from plain X–ray images using anteroposterior angulation, lateral angulation, and axial angulation views. The translational parameters are measured in a similar way. The frame itself is described by the proximal and distal ring diameters and the neutral frame height. The four remaining parameters are obtained in clinic and measure the location and axial rotation of the reference bone fragment with respect to the reference ring; the measurement of these four frame offset parameters is described by Taylor [8]. The Taylor spatial frame is kinematically equivalent to the Stewart platform, which is fully coupled (Stewart [7]); hence, any changes in the length of any one strut results in changes to all six strut lengths. The 13 parameters are used by the computer program supplied by the manufacturer of the frame to generate the six specific strut lengths and the daily schedule of adjustments that must be made to the struts by the patient (Taylor and Paley [9]).

There are three standard methods of surgically mounting the spatial frame. The chronic deformity–correction method requires that the surgeon attach the deformed frame (which would mimic the deformity) to the patient; the deformity is fully corrected once the frame reaches its neutral shape with all six struts having equal length. Alternatively, the rings–first method of deformity correction mounts the rings to the patient prior to attaching the struts. Finally, the residual deformity–correction method simply compensates for any residual deformity which may exist after either of the first two methods is used. In each of these methods, the surgeon mounts the rings perpendicular to the weight-bearing axis of the limb under fluoroscopic guidance using either Steinman pins or flexible tensioned Kirschner wires and centers the frame on the bone (Taylor and Paley [9]).

2.2 Computer–Assisted Technique

Our proposed technique modifies conventional approaches to deformity correction using the Ilizarov method in four fundamental ways:

1. The need for the surgeon to preoperatively measure the 13 frame parameters is removed.
2. The performed correction is based on the actual location of the frame with respect to the anatomy; any translational or angular problems that occur while mounting the frame are compensated for immediately thereby potentially removing the need for residual correction.
3. The correction is calculated based on 3D coordinates from CT data rather than measured from multi–planar radiographs.
4. The rings do not have to mimic the deformity; we essentially bypass the “chronic deformity correction” step to the “total residual correction” phase.

Unlike the computer–assisted method described by Iyun *et al.* [3], our method allows the surgeon to use any configuration of Rancho cubes, pins and wires.

We performed a small number of experiments using tibial phantoms (Sawbones, Pacific Research Laboratories, Inc., Vashon, Washington, USA). Our apparatus consisted of an Optotrak optical tracking system (Northern Digital Inc., Waterloo, Ontario, Canada) dynamic reference bodies (DRBs) attached to the proximal and distal ends of the tibia phantom, a tracked surgical probe, and 5 tibia phantoms[1].

For each of the tibia phantoms, a 3D surface model was constructed from CT data. Planning software was used to plan the necessary correction (a normal bone phantom was deformed in an arbitrary way or a deformed phantom was corrected). The Taylor spatial frame was mounted to the bone phantom using tensioned Kirschner wires and Steinman pins. Note that we could have chosen to intraoperatively guide the placement of the rings; however, for the purposes of this study, we chose to mount the rings arbitrarily in order to demonstrate that we can compensate for errors in frame placement. A DRB was attached to the proximal and distal ends of the tibia phantom. We registered the bone phantom to the 3D model using a registration algorithm based on Besl and McKay’s [1] ICP algorithm. Approximately 20 registration points were collected from the osteotomy region as well as from other surfaces that could be easily digitized percutaneously, such as the shaft and medial malleolus of the tibia. We then digitized three well–defined points on each ring of the frame. Using the ring measurements and the registration transformation, we computed the location of the rings in CT coordinates. Using the planned transformation of the mobile proximal fragment, we transformed the location of the proximal ring to its planned corrected location and calculated the necessary strut lengths. The tibia phantom was then cut and distracted by changing the strut lengths to those calculated by our model. Figure 1 demonstrates the Taylor spatial frame after correction is achieved. We chose three types of corrections which are visualized in Figure 2.

[1] We were limited to a small phantom study because our apparatus is used clinically by our affiliated hospital.

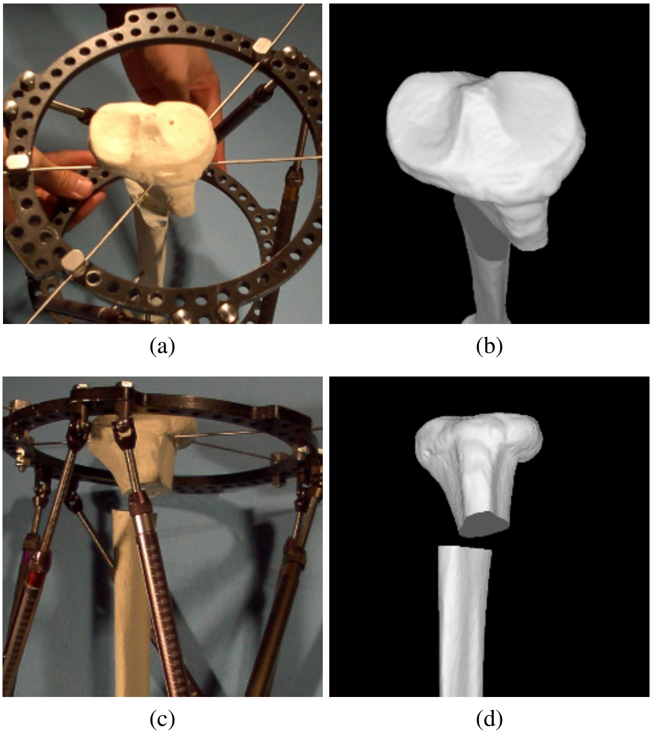

Fig. 1. Frame after correction in (a) axial and (c) lateral views and corresponding computer model of the planned correction in (b) axial and (d) lateral views

(a) (b) (c)

Fig. 2. The three six–degrees–of–freedom planned corrections used in our experiments. The primary modes of correction were (a) axial rotation, (b) lateral opening wedge, and (c) medial opening wedge.

3 Results

We originally attempted to track the motion of the distracted proximal end with respect to the distal end by tracking both ends of the phantom, but we could not reliably

Table 1. Alignment errors between planned and performed corrections

Correction	Rotational Errors (deg)				Translational Errors (mm)			
	θ	ϕ	δ	Total	x	y	z	Total
axial rotation	0.7	1.2	-4.2	4.4	-1.4	-1.2	1.3	2.23
lateral wedge	0.3	-0.2	0.7	0.78	-0.1	0.8	0.1	0.84
lateral wedge	-1.1	-0.2	1.4	1.82	7.1	-2.2	0.7	7.50
medial wedge	1.9	0.8	1.1	1.32	-0.9	-3.5	-2.5	4.37
medial wedge	-0.4	0.1	1.1	1.16	2.8	6.5	1.3	7.22

maintain fixation of the reference targets during the cutting and distraction processes because of the intense vibration associated with the cutting process. Instead, we digitized anatomic landmarks along with widely spaced registration points P and D separately from the proximal and distal ends, respectively, not restricting ourselves to surgically accessible surfaces. The registration transformation $\mathbf{T}_{\mathrm{D,CT}}$ of the distal end to CT coordinates was calculated and applied to the proximal registration points. The transformed proximal points $P' = \mathbf{T}_{\mathrm{D,CT}}P$ were registered to CT coordinates to obtain the transformation $\mathbf{T}_{\mathrm{P',CT}}$, and the displacement of the proximal end with respect to the distal end in CT coordinates was the inverse of this transformation $\mathbf{T}_{\mathrm{PD,CT}} = \mathbf{T}_{\mathrm{P',CT}}^{-1}$.

The rotation component $\mathbf{R}_{\mathrm{PD,CT}}$ of $\mathbf{T}_{\mathrm{PD,CT}}$ was compared to the rotation component $\mathbf{R}_{\mathrm{plan}}$ of the planned correction $\mathbf{T}_{\mathrm{plan}}$ by computing the difference in rotation $\boldsymbol{\Delta}$ where $\mathbf{R}_{\mathrm{PD,CT}} = \boldsymbol{\Delta}\mathbf{R}_{\mathrm{plan}}$ and converting $\boldsymbol{\Delta}$ to its screw representation; the rotation about the screw axis was the total angular error. We also calculated errors using Taylor's rotation matrix (Iyun *et al.* [3]) $\mathbf{R}_{\theta,\phi,\delta}$ where θ, ϕ, and δ were the projected angles of rotation measured in the anteroposterior, lateral, and axial views. The error in translation was taken to be the difference between the center of the proximal ring under $\mathbf{T}_{\mathrm{PD,CT}}$ and $\mathbf{T}_{\mathrm{plan}}$. All error measurements are tabulated in Table 1.

Retrospectively, we computed the uncertainty of the registration parameters for the axial deformity case by using a particle filter as part of the registration algorithm, de-

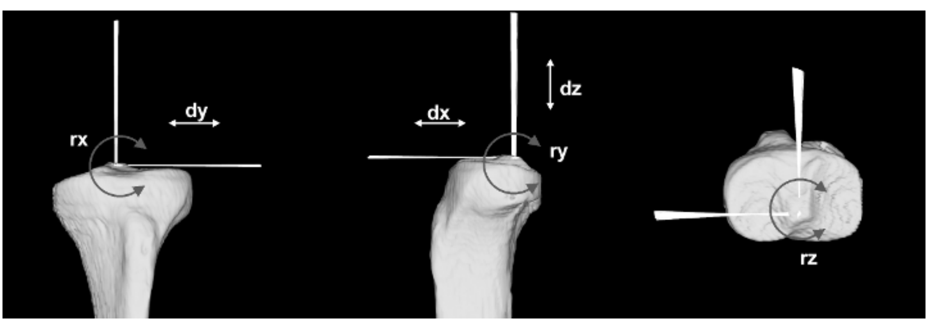

Fig. 3. Uncertainty in the location and orientation of the mobile proximal fragment for the axial rotation case. The total range of rotational uncertainty was 1.3° about the anteroposterior (AP) axis (rx), 1.3° about the mediolateral (ML) axis (ry), and 5.4° about the long axis (rz) of the fragment. The total range of translational uncertainty was 3.0mm along the AP axis (dx), 2.5mm along the ML axis (dy), and 3.9mm along the long axis (dz).

scribed by Ma *et al.* [10]. This algorithm produced a sampled distribution of the registration parameters rather than a single point estimate. The distribution of registration transformations was used to predict the range of the expected location and orientation of the mobile fragment. Figure 3 illustrates what happens to the three anatomical axes of the mobile fragment when the distribution of registration transformations is propagated through the planned correction transformation.

4 Discussion

It appears that the proposed method successfully implements the Ilizarov method of deformity correction using the Taylor spatial frame with computer assistance. The accuracy of our computer–assisted technique is better than the previous computer–assisted technique by Iyun *et al.* [3], which reported mean rotational and translational error of 3.2 degrees and 5.4 degrees, respectively. The major source of error in our method lies in the mechanical loading of the bone phantom when mounting the frame, which resulted in some strain of the phantom; the stress was released when the phantom was cut, displacing the bone fragments in the transverse (XY) plane. This phenomenon does not occur in a clinical setting. In the case of the large axial rotation correction, the final configuration of the frame was very unusual. Consequently, we found that there was significant rotational laxity about the vertical axis greater than our reported correction error of -4.2 degrees. Since we were simulating a deformity rather than a correction in this case, the laxity we observed would not occur clinically after a correction.

The primary disadvantage of our method is that a preoperative CT scan of the patient is needed, which is not generally required by the conventional surgical technique, in order to construct the 3D computer model. Furthermore, generating computer models and preoperative plans can be labor intensive. However, manually computing the 13 frame parameters in the traditional method requires approximately one hour to complete. Indeed, surgeons are conditioned to planning corrections based on bi–planar radiographs rather than 3D models; hence, it is unclear whether surgeons would be willing to visualize the necessary corrections in 3D. Finally, our method does not rely on the existing clinically used software provided by the frame manufacturer; therefore, significant testing is required to ensure the correctness of our system. A weakness of this study is the small sample size used in our experiments; we are attempting to perform more experiments as clinical conditions permit.

In clinical practice, the preferred method of registration would probably be from fluoroscopic images to the CT volume or anatomical atlas. We note that the registration algorithm would need to cope with occlusion artifacts caused by the presence of the metal rings of the frame. If we were able to register to an atlas, we would be able to use this method for trauma cases as this would eliminate the need for a CT scan. Registration remains the single point of failure in this method.

Practitioners of Ilizarov's method for deformity correction using the Taylor spatial frame admit that there is a steep learning curve in using the frame. It has been shown by Feldman *et al.* [2] that increased surgical experience with the system decreases the complication rate and increases the accuracy of correction using the frame. This is in part due to the fact that it is difficult to accurately measure the 13 frame parameters and to mount the frame without some residual rotational and translational errors. Our technique aims to reduce complications due to these factors by preoperatively planning the desired correction directly and reducing the possibility of errors introduced during surgery by calculating the correction based on the actual location of the frame with respect to the anatomy. Moreover, the surgeon has greater flexibility in choosing the position of the rings since this technique does not depend on placing the rings in a particular orientation. This relatively new approach of bypassing the "chronic deformity correction" stage directly to the "total residual correction" step is reported by Feldman *et al.* [2].

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