Biomedical Paper

Computer-Based Periaxial Rotation Measurement for Aligning Fractured Femur Fragments from CT: A Feasibility Study

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ABSTRACT
A new computer-based method for measuring periaxial rotation of healthy and fractured femurs from preoperative CT during closed femoral fracture reduction surgery is described. The method provides a comparative quantitative measure to align the distal and proximal femur fragments based on periaxial rotation. The periaxial rotation is defined in terms of patient-specific bone features. An algorithm for automatically extracting these features from the CT based on this definition has been developed. The algorithm extracts the condyle landmarks and neck axis of the healthy bone, determines its periaxial rotation, and extrapolates this data, assuming mirror symmetry between the healthy and fractured bones, to measure periaxial rotation between the fractured fragments. Unlike existing techniques, the method requires minimal user intervention. In a feasibility study, the method was applied to five dry femurs and one patient data set, and simulated a reduction based on the periaxial measurements with satisfactory results. The experiments showed the measured angle on the fractured femur to be within 1–4.5° of that of the healthy bone. Comp Aid Surg 7:332–341 (2002).

Key words: **computer-aided orthopedic surgery; femoral fracture reduction; periaxial rotation measurement**

INTRODUCTION

Closed intramedullary nailing is currently the procedure of choice for reducing long-bone fractures.[1] It restores the integrity of the fractured bone by means of a nail inserted into the medullary canal. The concept behind closed fracture surgery is to perform internal fixation of the fracture without surgically opening the fracture site, thereby avoiding additional damage to the already traumatized area. In closed intramedullary nailing, the nail is inserted through an opening close to the piriformus fossa in the proximal part of the bone. The surgeon manually aligns and orients the bone fragments by applying external pressure to the leg. He then inserts a guide wire and drives in the nail. In most cases, lateral proximal and distal interlocking screws are inserted to prevent fragment rotation and bone shortening. The procedure is performed under X-ray fluoroscopy, which is used to view the

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position of bone fragments, surgical tools, and implants. Many fluoroscopic images are necessary, especially during distal locking.[2–4]

An important issue in closed intramedullary nailing surgery is the correct alignment of the periaxial rotation of the distal and proximal fragments of the fractured femur. Correct alignment is necessary to ensure optimal postoperative function. In the current standard technique, the surgeon performs the alignment by making a qualitative assessment of the fragments' position on uncorrelated intraoperative fluoroscopic images. The surgeon compares them with contralateral preoperative X-rays or with intraoperative fluoroscopic images of the healthy femur. The proximal and distal bone fragments are then manipulated in an attempt to achieve a symmetric result. This procedure is lengthy, error prone, results in cumulative radiation exposure for the surgeon, and is dependent on the surgeon's skill.

The potential consequences of periaxial rotation malalignment are pain and secondary degenerative joint damage. The literature defines periaxial malalignment to be an angle value which differs by more than 9–15° with respect to the contralateral femur.[5,6] A study of 120 intramedullary femoral fracture reduction cases operated with the conventional technique found periaxial rotation malalignment of more than 15° in 19% of cases.[6]

Providing an accurate measure of the fractured femur's periaxial rotation to guide the surgeon in correctly aligning the distal and proximal fragments can potentially reduce the error rate. In addition, it can reduce the procedure time and the surgeon's cumulative exposure to radiation, because the frequent use of fluoroscopy to assess the position of bone fragments is no longer necessary. However, obtaining such a measurement raises several questions. First, because the physiological periaxial rotation value of the fractured bone is not available, what should be the target value? Should it be symmetrical to the one for the healthy bone (assuming no deformities), or should it be based on an estimate of that value prior to the fracture? Second, how is the periaxial rotation value of a fractured femur defined? Should it be relative, with respect to the healthy femur, or absolute, with respect to an estimate of the value prior to the fracture? Third, what imaging modalities should be used to measure it—preoperative X-rays, a CT study, or intraoperative X-ray fluoroscopic images?

Most previous research addressed the problem of establishing methods for accurately measuring periaxial rotation (also referred to as anteversion or antetorsion) of healthy femurs using X-rays,[7] CT scans,[8] and computer-reconstructed models.[9] The measure of periaxial rotation is not uniquely defined, and there is disagreement as to the best way to measure it. Consequently, most efforts have been focused on defining periaxial rotation and developing measurement protocols.

We distinguish between two approaches to periaxial rotation measurement: absolute and relative. In the absolute approach, the femur's periaxial rotation is measured directly from the images. This is commonly used in total hip replacement surgery to determine preoperatively the type and location of the implant and cup. In the relative approach, the periaxial rotation of one femur is measured relative to the other femur. This is commonly used in femoral fracture reduction to align the distal and proximal fragments according to the periaxial rotation of the healthy femur. The drawback of the absolute approach for femoral fracture reduction is that the periaxial rotation is not defined for the fractured femur. In the relative approach, the fractured femur periaxial rotation is computed intraoperatively based on the characteristics of the healthy femur.

Several methods for absolute periaxial rotation measurement have been described in the literature.[10–14] Egund and Palmer[10] described a method that consists of acquiring several CT slices at selected locations, manually extracting geometric features from those slices, defining a reference plane and a plane though the femoral head from the features, and measuring periaxial rotation as the angle between the plane normals. Hermann and Egund[11] proposed to measure periaxial rotation from three CT slices and from fluoroscopic images of the whole femur at predetermined viewpoints. This method requires significant manual user intervention. In another article,[12] Hermann and Egund determined that femur positioning on CT slices does influence the femoral periaxial rotation measurement, and concluded that a full 3D reconstruction of the bone from the CT scans is necessary to compensate for nonstandard bone positioning.

Comparison studies of alternative methods of measuring femoral periaxial rotation with radiographic methods have also been conducted.[13,14] Murphy et al.[13] compared four different definitions of periaxial rotation measurement and concluded that the "table-top" method for locating the condylar plane (which we refer to as the table-top plane), is the simplest, most reproducible, and most similar to the clinical method of measurement. Sugano et al.[14] compared various definitions and measurement procedures based on different data for periaxial rotation. The study provided a quantitative statistical evaluation of each of the methods by comparing the results to a periaxial rotation value (termed "true anteversion") measured by positioning a 3D model reconstructed from CT slices of the femur in a position close to that used in the classical clinical method of measuring periaxial rotation manually. The study concluded that most methods either overestimate or underestimate the average and standard deviation of the method compared to a full 3D reconstruction.

Hofstetter et al.[15] described a surgical navigation system that assists surgeons in femoral fracture reduction based on fluoroscopic images only. Relative periaxial rotation is estimated from contralateral images and from six manually selected landmarks in anterior–posterior and lateral fluoroscopic images, and is updated in real time during the procedure. The long axes of the healthy and fractured femurs are independently constructed from those points. The key advantage of this method is that it does not require a preoperative CT study; it uses readily available fluoroscopic images. However, the method does require manual intraoperative landmark selection, which is time consuming and whose accuracy is surgeon dependent. Because the fragment axes are computed independently, the measurement does not account for the natural arching of the femur, thereby introducing a bias in the measurement. Also, the absolute periaxial rotation value of the healthy femur is the only value used as a reference for the fractured femur reduction.

MATERIALS AND METHODS

We describe a CT-based method for assisting surgeons in correctly aligning periaxial rotation of the distal and proximal fragments of the fractured femur during closed femoral fracture reduction surgery. The method provides both comparative and absolute periaxial rotation values for the healthy and fractured bones, based on the premise that the desirable periaxial rotation value should be symmetrical to that of the healthy bone while also accounting for the arching of the fractured femur.

The method has been incorporated into FRACAS,[16] a computer-integrated system specifically developed for closed long-bone fracture reduction. The system replaces uncorrelated static fluoroscopic images with a virtual-reality display of 3D bone models created from preoperative CT and tracked intraoperatively in real time (Fig. 1).

We chose to base our method on preoperative CT scans, which are not routinely required for closed medullary nailing in most hospitals. This deviates from current practice and introduces additional cost. Our rationale was that these disadvantages are compensated for by the advantages of the method. First, the literature and our studies indicate that CT-based methods are the most accurate because they derive measurements from spatial models. Second, the radiation exposure of the surgeon and patient is reduced, because the navigation is performed with bone-fragment models. Third, the reduction time can be shortened, because the reduction is performed with spatial views instead of planar ones. Fourth, the models derived from the CT study are used for other purposes, such as diagnosis, preoperative nail selection, and visualization. Finally, we observe a trend toward increased use of CT as a diagnostic tool in trauma, as in our hospital. Of course, a comparative clinical study is necessary to substantiate these claims.

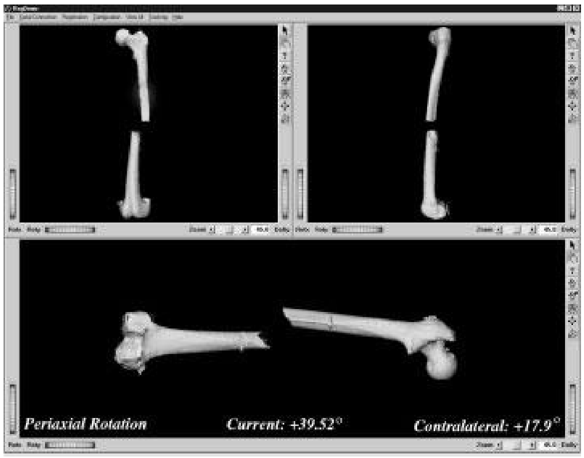

Fig. 1. Screen of the computer-based periaxial rotation alignment system used for intraoperative fracture reduction. Simultaneous frontal (top) and lateral (bottom) spatial views are shown, together with the current and contralateral periaxial rotation values.

Periaxial Rotation: Definition

We define periaxial rotation in terms of simple geometric relations between four patient-specific bone features and a plane: the two extremal condyle points, the long axis of the femur, the femoral neck axis, and the "table-top plane," as shown in Figure 2. The extreme dorsal points of the medial and lateral condyles are the points in contact with a plane parallel to the long femoral axis. They are the two points that touch the table plane when the femur is placed on a table with its long axis parallel to the plane. The two condyle points and the long

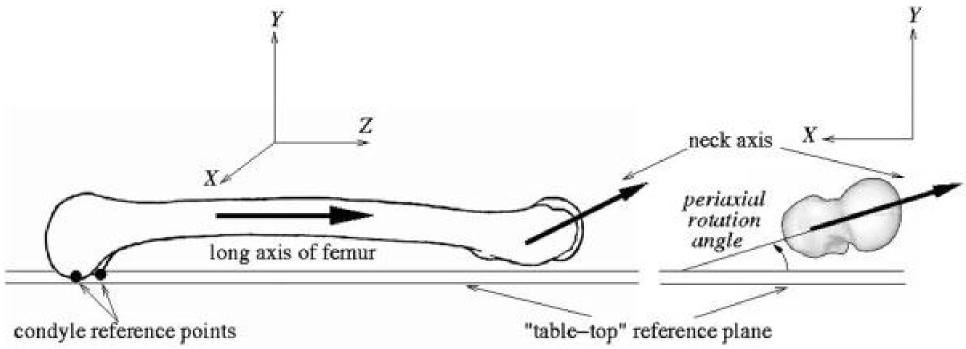

Fig. 2. Definition of periaxial rotation: lateral (left) and frontal (right) views. The *XYZ* orthogonal coordinate system in which the angle is measured is defined as follows. The *XZ* plane is parallel to the table-top plane, which is the plane that contains the condyle reference points and is parallel to the femur long axis. The *Z* axis coincides with the long axis of the femur. The *Y* axis is perpendicular to the *XZ* plane and is oriented upwards. The periaxial rotation angle is the angle of the neck axis projection on the *XY* plane measured with respect to the *XZ* (table top) plane.

axis uniquely define the configuration of the femur and thus the orientation of the femoral neck axis.

We define the periaxial rotation angle with respect to the *XYZ* orthogonal coordinate system of each bone, which is defined as follows. The *XZ* plane is parallel to the table-top plane, which is the plane that contains the condyle reference points and is parallel to the femoral long axis. The *Z* axis coincides with the long axis of the femur. The *Y* axis is perpendicular to the *XZ* plane and is oriented upwards. The periaxial rotation angle is the angle of the neck axis projection on the *XY* plane measured with respect to the *XZ* (table-top) plane.

A key property of this definition is that it can be directly extended to a fractured femur: the table-top plane is defined by the distal fragment and its long axis. The femoral neck axis is defined by the proximal fragment. The periaxial rotation angle of the fractured femur is the angle between the axis of the femoral neck and the table-top reference plane, provided both are in the same coordinate system.

We associate an orthogonal coordinate system *XYZ* to the healthy femur and to the distal and proximal fragments of the broken femur, as shown in Figure 3. For the healthy femur and the distal fragment, the *Z* axis coincides with the long-bone (fragment) axis and is oriented to point toward the femoral head for the healthy femur, or toward the condyles for the distal fragment. For the proximal fragment, the *Z* axis coincides with the long fragment axis and is oriented toward the femoral head. In all cases, the *X* axis is parallel to the table-top plane, and points away from the femoral head. The *Y* axis is always oriented upwards so as to define a right (left) axis system for the right (left) leg bones. This construction embodies the assumption that the left and right femurs of a normal patient are approximately mirror-symmetric about the *YZ* plane. The coordinate frame origins are arbitrarily chosen to be the centroids of the bones. This choice does not influence the periaxial rotation angle computation.

Protocol

The FRACAS protocol for closed intramedullary nailing proceeds as follows.[16] After the patient

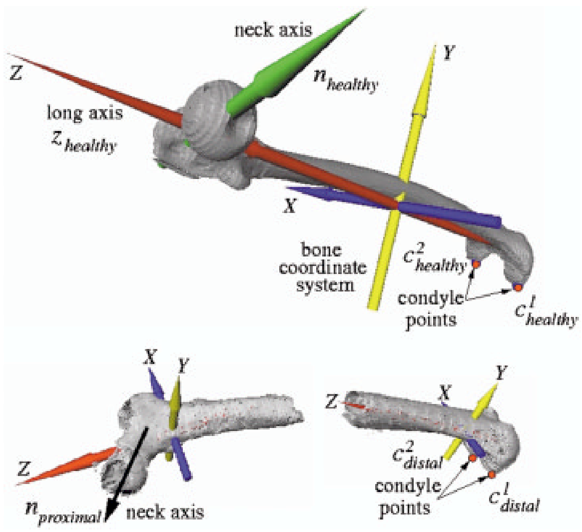

Fig. 3. Coordinate frames and features of the healthy femur (above), proximal fragment (bottom left), and distal fragment (bottom right). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

arrives at the hospital and is stabilized, a CT study of both legs is taken. The CT slices are no more than 3 mm apart in the proximal and distal area (enough to include the femoral head and the condyles) and 5 mm apart in the shaft area. The CT study is downloaded to the computer in the surgeon's office. The computer automatically builds geometric surface models of the healthy femur and the proximal and distal fragments using standard segmentation and surface reconstruction techniques such as Marching Cubes. It also identifies their geometric features, and computes the periaxial rotation value of the healthy femur. The surgeon then visualizes the healthy and fractured bones, interactively selects the proximal and distal fragments, and chooses the nail to be inserted. This preoperative planning phase takes 15 min on average.

Shortly before surgery, the computer with the data loaded onto it is introduced into the operating room, together with the calibration and optical tracking devices. The optical equipment is installed and the C-arm is calibrated. Once the patient has been prepared, a tracking plate is attached to the proximal and distal bone fragments. The intraoperative situation is then registered to the preoperative models with a few fluoroscopic images. This establishes a common reference frame (the camera) and allows the position and orientation of the fragments to be followed in real time, their display as they appear in the patient's leg, and computation of the current value of their periaxial rotation, as shown in Figure 1. The surgeon uses the views and the periaxial rotation value to bring the bone fractures into alignment without further use of fluoroscopy. The surgeon then inserts the guide wire and nail, and locks the nail proximally and distally as required.

Computation of the Periaxial Rotation Angle

We now describe an algorithm for computing the periaxial rotation angle of the healthy and fractured femurs. The inputs are three surface bone models (triangular surface meshes) of the healthy femur and the distal and proximal fragments of the fractured femur constructed from the CT data set. The outputs are the geometric bone features (femoral long axis, condyle landmarks, femoral head, and neck axis, table-top plane) and the measurements of the periaxial rotation of the healthy and broken femurs.

The method consists of three steps. First, the principal axes of the healthy and fractured bones are computed using the Principal Axis Transformation (PAX) technique (see below).[17] Second, the geometric features of the healthy femur are automatically extracted, as are those of the proximal and distal fragments by using the healthy femur as reference (Fig. 4). Third, the periaxial rotation value of the healthy and fractured bones is computed and displayed, together with the bone models, to guide the surgeon during the fracture reduction.

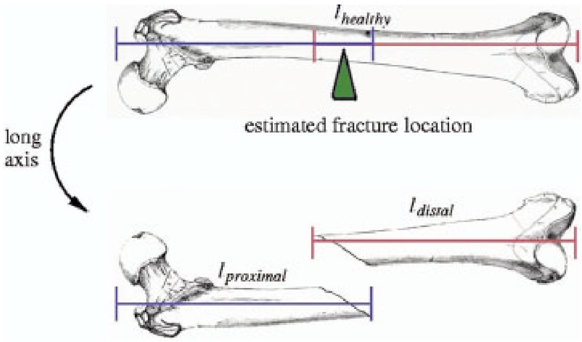

Fig. 4. Fracture interpolation on healthy bone. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

Computation of the Principal Axes of the Bones

As in clinical practice, we determine the bones' principal axes from the geometry of their outer surfaces. For this purpose, we use the PAX technique. PAX computes a coordinate system with three orthogonal axes corresponding to the major axes of mass distribution of an object.[17] The principal axis is the one with the highest variance of points. Each major axis is associated with an eigenvalue of the object's mass covariance matrix that measures the variance of mass distribution along the axis direction. High eigenvalues indicate a greater distribution of mass along that axis.

In our case, the objects are geometric surface models consisting of uniformly sampled surface points extracted from the CT data set. To find the geometrical long bone axes, we assign a unit mass value to each point in the bone surface and use the PAX method to find the axes: the axis with the highest eigenvalue is the long axis of the bones, both healthy and fractured. The principal axes are the eigenvectors of the covariance matrix of the model's points, given by the matrix

$$\sum_{i=1}^{n} \begin{bmatrix} v_x^i\, v_x^i & v_x^i\, v_y^i & v_x^i\, v_z^i \\ v_x^i\, v_y^i & v_y^i\, v_y^i & v_y^i\, v_z^i \\ v_x^i\, v_z^i & v_y^i\, v_z^i & v_z^i\, v_z^i \end{bmatrix}$$

where (v_x^i, v_y^i, v_z^i) are the coordinates of point i relative to the model's center of mass and the sum is over all n points of the bone model. The three principal axes form an orthonormal basis of the Euclidean space. The orientation and labeling of the axes is then defined as shown in Figure 3, which is consistent with the coordinate system of the CT scanner.

Extraction of Geometric Features

The algorithm extracts the two extreme dorsal condyle points and the axis passing through the femoral neck of the healthy bone from its surface model as follows. The extreme dorsal condyle points are the lowest points with respect to the Y axis, which lie on opposite sides of the YZ plane. The femoral neck axis is the principal axis found by PAX on the region upwards of the lesser trochanter (femoral head and neck). The surface points in the femoral region are found by "cutting" the proximal femoral fragment model with a plane at the root of the lesser trochanter and parallel to the XY plane (the beginning of the lesser trochanter is approximately determined by comparing the cross-section bone contour length and width ratio changes in five consecutive CT slices). The periaxial rotation value of the healthy bone is then computed from the condyle landmarks and the femoral neck axis as the angle between the plane normal and the femoral neck axis. The relevant geometric features of the fractured femur fragments are extracted in an identical manner. The condyle landmarks and long axis are extracted for the distal fragment, and the femoral neck axis for the proximal fragment.

The algorithm estimates the approximate location of the fracture on the healthy bone by assuming mirror symmetry between the healthy and fractured bones, splitting the healthy bone model at that location, and calculating the principal axes for the interpolated distal fragment as shown in Figure 4. The algorithm calculates the rigid transformation that takes the interpolated distal-fragment coordinate system to the real distal-fragment coordinate system. It then transforms the femoral long axis of the healthy femur to the distal-fragment coordinate system (as given by PAX) using this transformation, defining it as the interpolated long axis of the fractured femur. The table-top reference plane for the distal fragment is defined as the plane that contains the distal-fragment condyle landmarks and is parallel to the interpolated long axis.

The geometric features on the bones, the condyle landmarks, and the femoral neck axis of the healthy and fractured bones are computed directly from the bone-model surface points in the bone principal axes coordinates whose origin is the center of mass. The periaxial rotation measurement is computed with respect to the table-top reference plane that contains the condyles and is parallel to the long axis of the bone.

The condyle landmarks, which are the extreme dorsal points on the medial and lateral condyles, are the lowest points relative to the Y axis that are on opposite sides of the YZ plane. The medial and lateral condyles are denoted as $\{c^1_{healthy}, c^2_{healthy}\}$ and $\{c^1_{distal}, c^2_{distal}\}$ in the healthy and broken bones, respectively.

The neck axes of both the fractured and healthy (interpolated) proximal bone segment are computed by isolating the upper region of the proximal bone containing the femoral head and the lesser trochanter, and applying PAX to the model points in that region. The resulting long axis estimates the position of the neck axis. The proximal neck axes of the healthy and broken femurs are denoted as $n_{healthy}$ and $n_{proximal}$, respectively.

The table-top plane $P_{healthy}$ for the healthy bone is defined as the plane that contains its condyles, $c^1_{healthy}$, $c^2_{healthy}$, and is parallel to its long axis, $z_{healthy}$ (Z axis). The algorithm proceeds in five steps:

1. Estimate the fracture location on the healthy bone. That is, the location of the fracture as if the fractured bone were correctly aligned, reflected, and overlaid on the healthy bone. This estimated location L is computed from the lengths of the proximal fragment $l_{proximal}$, the distal fragment l_{distal}, and the healthy bone $l_{healthy}$ along their long axis Z:

$$L = \tfrac{1}{2}\left[(l_{healthy} - l_{proximal}) + l_{distal}\right]$$

2. Split the healthy bone model at the estimated fracture location with a plane parallel to the XY plane at the computed location L along the Z axis. This yields interpolated proximal and distal fragments. All bone surface points to the left of the plane (positive inner product with the Z axis) belong to the proximal fragment, while all points to the right of the plane belong to the distal fragment. The long axes of these virtual fragments are computed with PAX and labeled

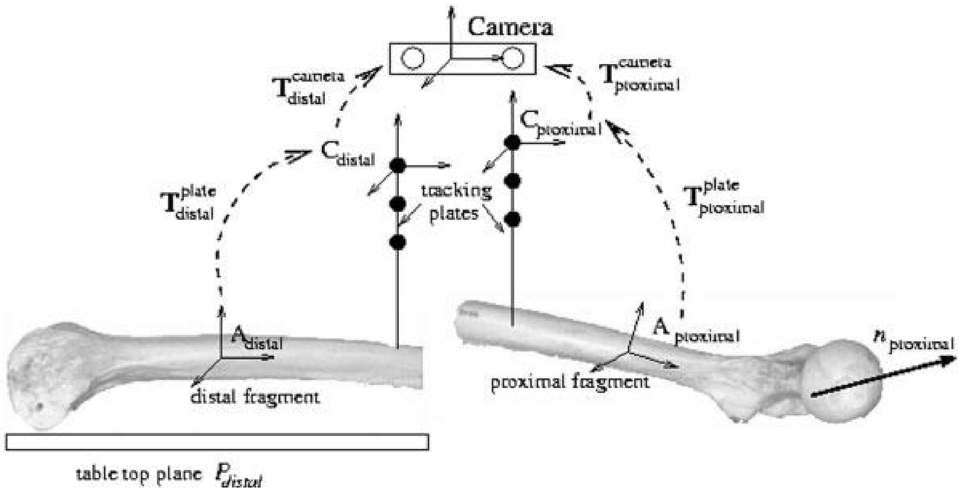

Fig. 5. Coordinate transformations for bone fragments.

as the fragments' Z axes. The X and Y axes are then oriented as shown in Figure 3.

3. Compute the rigid transformation $T^{idistal}_{distal}$ that aligns the principal axes of the interpolated distal fragment to the principal axes of the real distal fragment (Figure 5). This transformation is defined as $T^{idistal}_{distal} = T_{distal} * (T^{idistal})^T$, where T_{distal} and $T^{idistal}$ are the rigid transformations from the world coordinates to the principal axes of the real and interpolated distal fragments, respectively. The transpose of $T^{idistal}$, denoted as $(T^{idistal})^T$, performs the reflection.
4. Compute the interpolated long axis along the distal fragment, $z'_{distal} = T^{idistal}_{distal}\, z_{healthy}$, by applying the transformation $T^{idistal}_{distal}$ to the long axis of the healthy bone z_{healthy}. The table-top plane of the distal fragment, P_{distal}, is the plane containing the distal fragment condyles c^1_{distal}, c^2_{distal} and the interpolated long axis z'_{distal}.
5. Compute the neck axis for the proximal fragment $n_{proximal}$.

Periaxial Rotation Computation and Update

The healthy bone's absolute periaxial rotation angle value is the angle between the unit neck axis vector $n_{healthy}$ projection on the XY plane and the table-top plane $P_{healthy}$:

$$\alpha_{healthy} = 90 - \arccos\,(\text{projection}(\mathbf{n}_{healthy}, XY)\ .\ \mathbf{p}^{+}_{healthy})$$

where $p^{+}_{healthy}$ is the normal to the plane $P_{healthy}$ and . is the vector dot product.

The periaxial rotation value for the broken femur is computed similarly, using the normal to the table-top distal plane P_{distal} and the proximal fragment femoral neck axis $n_{proximal}$:

$$\alpha_{broken} = 90 - \arccos\,(\text{projection}\,(\mathbf{n}_{proximal}, \text{XY})\ .\ \mathbf{p}^{+}_{distal})$$

Note that, because both the distal and proximal fragments move, the value changes. For this value to be meaningful, the vectors must be with respect to the same coordinate frame, which is the camera coordinate frame.

The fragment positions with respect to the tracking camera are related to the camera coordinate frame as shown in Figure 6. Each fragment has its own local coordinate system, A_{distal} and $A_{proximal}$, which was derived from the CT data. Each tracking plate attached to the fragments has its coordinate system, C_{distal} and $C_{proximal}$. Their location with respect to the camera coordinate system, *Camera*, is given by the transformations T^{camera}_{distal} and $T^{camera}_{proximal}$, which are provided by the tracking system. The transformations T^{plate}_{distal} and $T^{plate}_{proximal}$ are computed once by an initial registration and do not change during the reduction.

EXPERIMENTAL RESULTS

We designed and conducted experiments to determine the usefulness of our method in fracture reduction. Because there is no gold standard for determining the correct absolute value of the periaxial rotation, we compared the value of the broken femur to the value of its mirror image. When the

Fig. 6. Experimental setup for fracture reduction based on periaxial rotation values. The surgeon on the right manipulates the fragments without seeing them according to the indications of the surgeon on the left, who can see the bone-fragment models and periaxial rotation value on the screen.

reduction is successful, the periaxial rotation values should be identical.

We obtained scans of one actual fracture case and five dry femurs, and performed periaxial rotation measurements on them. The CT slices are at most 3 mm apart in the proximal and distal areas (enough to include the femoral head and the condyles), and at most 5 mm apart in the shaft area. For the real case, both left and right femurs were available. For the dry femurs, we created a mirror image of each to obtain the contralateral bone and virtually broke it (by splitting the model) to obtain distal and proximal fragments.

To determine the effectiveness of our periaxial measurement method for fracture reduction, the following *in vitro* experiment was performed using five whole dry femurs and a physical fracture simulator device as shown in Figure 6. In each case, we first CT scanned the femur, constructed a surface model of it, and then created a reflected model. Next, we physically broke the femur into two fragments, CT scanned both fragments at the same resolution, and constructed models of them. We extracted the geometric features and computed periaxial rotation for the five models as described above. We then attached an optical tracking instrument to each fragment and registered each to its model using contact-based registration techniques.[19]

Once the model was registered, the surgeon was asked to correct the orientation of the fragments without directly seeing them, based only on the computed periaxial rotation values (as will be done in the operating room) (see Fig. 6). Once a satisfactory alignment between the fragments was obtained based on the displayed values, we compared it with the actual physical position of the bone fragments. In addition, we asked a surgeon to determine whether the discrepancy was acceptable. The experiment was repeated at different locations within a cube whose side length is about 1 m to ensure the spatial consistency of the measurement. In all cases, the fragments appeared to be well aligned, so the results were qualitatively satisfactory. The surgeons achieved alignment within a minute, even in the cases where one surgeon looked at the computer screen and guided an assistant who could not see it, as in Figure 6.

Table 1 shows the quantitative results of the experiments performed on the five dry femurs. The samples include bones with periaxial rotations ranging from normal (18.5°) to very high (34.2°). The average difference between the periaxial rotation value of the healthy bone and the value after reduction is 1.8° (range 0.6 to 4.4°). These results are well within the margin of error, which is acceptable in the intraoperative fracture reduction.

We also tested the accuracy and repeatability of the alignment and reduction based on the computed values. For this purpose, we rotated the proximal fragment around the long axis, increasing and decreasing the angle between the femoral neck axis and table-top plane, and then returning it to its

Table 1. Quantitative Results of Periaxial Rotation Measurement on the Five Femurs

Data set	Reference angle	Mean value	Standard deviation	Variation	Number of measurements
Right 1	18.5°	17.9°	0.6°	−0.6°	90
Left 2	25.0°	26.7°	0.8°	+1.7°	44
Left 3	34.4°	30.0°	0.6°	−4.4°	32
Right 4	19.4°	20.3°	0.9°	+1.5°	29
Left 4	21.2°	20.8°	0.4°	−0.8°	33

The first column indicates the reference periaxial rotation angle of the healthy femur. The second column shows the periaxial rotation angle of the fractured femur after the computer-assisted reduction. The third column shows the standard deviation, the fourth the variation, and the fifth the number of measurements performed.

aligned position. The periaxial rotation value increased or decreased as expected and returned to the original value with an error range of $\pm 0.5°$.

DISCUSSION

In contrast to previous approaches, our work is the first to provide a comprehensive and fully automated relative periaxial rotation measurement from preoperative CT. It provides a comparative measure of femur periaxial rotation before and after the fracture, rather than attempting to find an absolute measure of periaxial rotation or periaxial rotation only applicable to healthy femurs. We believe that this relative measure is the most useful one for restoring function and improving surgical outcomes. The emphasis is on precise and robust automatic location of geometric features in the bone models. Our preliminary experiments with patient data indicate that this is achievable, and that more accurate relative periaxial rotation measurements can be obtained. It remains to be seen whether the drawback of the additional preoperative CT study requirement is outweighed by the benefits of the new method.

As pointed out in the introduction, a variety of methods for periaxial rotation measurement have been reported in the literature.[7–14] However, most of these measure absolute periaxial rotation of the healthy femur, while we measure the relative periaxial rotation value of the fractured femur with respect to the healthy femur, so a direct comparison is not very meaningful. Suffice it to say that multislice CT-based methods are reportedly the most accurate, with an average error of $\pm 1°$, compared to an average underestimate of 10° with a single CT image.[13]

The published method that is closest to the one presented in this article is that of Hofstetter et al.,[15] which measures relative periaxial rotation based on a few intraoperative fluoroscopic X-ray images. That article reported an in vitro periaxial rotation error of $\pm 5°$ over normal femurs, which increased when the C-arm was misaligned. This constitutes a clear improvement over the conventional procedure. The method also significantly reduces radiation exposure. A study by Suhm et al.[20,21] showed that fluoroscopy-based navigation reduces the radiation exposure to about 10% of what is required in the conventional procedure.

In comparison to this earlier work, our method has the advantage that it does not depend on C-arm alignment and achieves a twofold accuracy improvement. In addition, the accuracy of the other method depends on the surgeon's manual intraoperative identification of landmarks in fluoroscopic images, which is error prone and subject to variability. However, our method requires acquisition of an additional preoperative CT data set, with resulting additional radiation exposure for the patient, and is subject to errors if the patient moves during the CT scan.

The advantages of our method are several. First, no additional images are required. The bone models are the same models used for navigation during surgery, which are derived from the preoperative CT scan. Second, no manual CT slice selection is required. The method automatically identifies the slices belonging to regions of interest where geometric features will be extracted. Third, the feature extraction from both the healthy and fractured femurs is fully automatic, which ensures robustness, repeatability, and accuracy. Fourth, the method is position-scan independent.

CONCLUSION AND FUTURE WORK

We have presented a new computer-based method for periaxial rotation measurement of healthy and fractured femurs from CT during closed femoral fracture reduction surgery. The method provides a comparative quantitative measure to align the distal and proximal femur fragments based on periaxial rotation. We define periaxial rotation in terms of patient-specific bone features and describe an algorithm for automatically extracting these features from the preoperative CT. The method has the potential to replace the current trial-and-error approach by a more consistent method that yields predictable results and reduces radiation exposure for the surgeon.

Our initial experimental results are encouraging, showing an improvement over published methods. It is planned to carry out the first in vivo test in the near future. We will use the traditional fluoroscopic validation method to qualitatively evaluate whether the periaxial rotation measurement combined with the visualization method reduces the reduction time and provides satisfactory results.

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