Skeletal landmarks for TKR implantations: Evaluation of their accuracy using EOS imaging acquisition system

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Summary
Introduction. — Lower extremity alignment remains one essential objective during total knee replacement. Implants positioning analysis requires selecting reliable skeletal landmarks. Our objective was to in vivo evaluate the precision of the implemented skeletal landmarks. This evaluation was based on multiple three-dimensional (3D) computer reconstructions of the lower extremity derived from an EOS\textsuperscript{®} biplanar low-dose X-ray system acquisition. A 3D angle measurement protocol was used.

Hypothesis. — Currently defined landmarks carry a tolerable uncertainty margin, which can still probably be further improved.

Material and methods. — Nine lower extremity 3D computer reconstructions were obtained from an EOS protocol based on seven simultaneous A–P and lateral views performed in standing position. A database was established by four operators; finally, building up a total of 99 in vivo 3D reconstructions of these nine lower extremities. Specific algorithms were used for such 3D reconstructions of lower extremities based on bone points and pre-identified contours on X-ray. Four femoral landmarks and four tibial landmarks were thus defined. For each bone and each landmark studied, a mean landmark for the 11 consecutive series elements was established. The deviation from each constructed landmark to the corresponding mean landmark was calculated based on the anteroposterior (x), longitudinal (y) and mediolateral axes (z), in translation (Tx, Ty, Tz) and in rotation (Rx, Ry, Rz). Uncertainty was estimated by the 95\% confidence interval (95\% CI).
Results. — The landmarks located at the middle of the segment joining the center of each posterior condyle and at the barycenter of the plateaux showed a greater reliability; these landmarks uncertainty (95% CI) of Tx, Ty, Tz was less than 1, 0.5, 1.5 mm for the femur and 1.5, 0.6, 0.6 mm for the tibia, respectively. The femoral landmarks using the center or posterior edge of the posterior condyles to define the mediolateral axis were retained; for rotations Rx, Ry, and Rz, uncertainty remained less than 0.3, 4, and 0.5°. All of the tibial landmarks had a comparable reliability in rotation, 95% of the Rx and Rz deviations were under 0.5 and 1.3°, respectively, with a mean error less than 1°. For the tibial rotation Ry, the mean error was greater (4°), with uncertainty (95% CI) at 11.2°. All tibial translations showed a mean error of 1 mm. The 3D implantation angles were measured on two patients using preoperative 3D skeletal reconstructions and 3D geometric models of the implants repositioned on postoperative EOS® knee X-rays.

Discussion. — The posterior condyles are rarely involved in the arthritic wear process, making them an anatomic landmark of choice in the analysis of the femoral component positioning. The femoral landmarks using the posterior condyles were sufficiently reliable for clinical use. However, the posterior contours of the tibial plateaux were less precise. The knees should be staggered from an anteroposterior perspective on the EOS® lateral images so that they can be visualized separately. The anatomic zones on which the skeletal landmarks are based are usually removed by the bone cuts, making it preferable to save the preoperative computer reconstructions to analyze the postimplantation 3D reconstruction.

Conclusion. — The lower extremity skeletal landmarks precision relates to the quality of the corresponding 3D reconstructions. Except for tibial rotation, all the translation and rotation parameters were estimated within a mean error margin inferior to 1.2 mm and 1.3°, respectively. Making the reconstruction algorithms more robust would render certain anatomic zones even more precise. Biplanar low-dose EOS® X-ray system is a tool of the future to generate 3D knee X-rays that can improve the evaluation and follow-up of total knee arthroplasty patients.

Level of evidence: level IV, diagnostic study.
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Introduction

Alignment of the morphotype and the precise orientation of total knee implants are essential to prevent wear of the polyethylene and ensure that the prosthesis is long lasting [1,2]. Computer-assisted surgery compared to conventional instrumentation has recently shown better radiological implantation angles [3–5] in reference to a 180° femorotibial mechanical axis in the frontal plane. Are the monoplanar goniometric measurements that are usually used precise enough to evaluate the 3D position of knee implants? Despite the standardization of radiographic protocols [6], measurement errors related to the influence of femur rotation on the radiographic projection of its mechanical axis are still possible. A 10° axial rotation provides a 4° error [7]. Two-dimensional digital images using software tools have made it possible to obtain reliable measurements more rapidly [8], but the landmarks used remain monoplanar and dependent on the radiographic view. Two-dimensional goniometric measurements are actually projected angles that vary depending on the patient’s position. A multidisciplinary collaboration between researchers (The ENSAM Biomechanics Laboratory in Paris, The Research in Imaging and Orthopedics Laboratory in Montreal, the Departments of Radiology and Orthopedics at Saint-Vincent-de-Paul Hospital in Paris, and Biospace Instrument) has recently developed a new imaging device called EOS® [9] whose main characteristics are the considerable reduction in X-ray dose (800–1000 times less than for tomodensitometry and ten times less than for conventional radiography) using gaseous detectors invented by Georges Charpak, which won him the Nobel prize in physics in 1992. Contrary to CT examination [10], the patient is standing on both feet. The EOS® system with its 3D reconstruction algorithms [11–16] made it possible to obtain 3D geometry of the bone piece based on two simultaneous biplanar X-rays with a surface precision comparable to that of CT. Using conventional stereoradiography on implanted knees, Nodé-Langlois [17] obtained a mean angle error less than 1°. The identification and choice of skeletal landmarks remain an indispensable prerequisite before angle measurements can be taken. The robustness of these landmarks, that is, their lesser or greater sensitivity to skeletal reconstruction uncertainty, is directly related to the anatomic references used to define them. Our objective was to evaluate the interobserver reliability of different skeletal landmarks placed on EOS® 3D reconstructions of the lower limb performed in vivo. A reliability study of the analysis of the 3D implantation angles was conducted on two cases based on the skeletal landmarks placed on the patient’s preoperative model.
Material and methods

Population

Acquisitions for the interobserver study
Seven frontal and lateral EOS® knee X-rays were acquired simultaneously in seven standing patients who had no gonarthrosis, for the purposes of reconstructing nine different lower limbs (four left and five right limbs).

Low-dose stereoradiography and digital acquisition with the EOS® platform

The patients were positioned standing on both feet in the EOS® cabin with the feet parallel and far enough apart so that the patient was stable and the image sufficiently clear for the measurements to be taken. In frontal images, to prevent superimposition of the radiographic contours of each knee's condyles and clearly show each ankle, the patient's feet were staggered (Fig. 1) along the anteroposterior axis. The metatarsal—phalanx joint of the big toe of the healthy forefoot was positioned in line with the middle of the arch of the opposite foot. Two perpendicular low-dose X-ray beams scanned the patient from the pelvis to the feet in less than 10 s, providing a simultaneous frontal and lateral EOS® knee X-ray in a calibrated environment (Fig. 2A and B).

Reconstruction algorithm

Automatic digitalization of the images allowed them to be integrated into the specific software environment, developed in collaboration with the ENSAM Biomechanics Laboratory in Paris and the ETS Imaging and Orthopedics Research Laboratory in Montreal. The non-stereo-corresponding point (NSCC) algorithm [13] provided 3D reconstruction of the lower limb based on the points and contours identified on the X-rays.

Construction of landmarks modeling implant alignment

The choice of the landmarks to be used for the implants and the skeleton of the lower limb took into account the implant geometry and the restrictions imposed by the mechanical axis. The detailed definition of these landmarks is shown in Fig. 3. Each landmark was based on a point to define the origin and two axes; the third axis was defined by the vectorial product of the two others. For the femur, the point retained for the proximal extremity was always the center of the femoral head approximated by a least squares sphere. The distal extremity was represented on a case-by-case basis by the center of the spheres representing the posterior condyles, the intersection of the diaphyseal axis with the trochlea, the barycenter of the points belonging to the condyles or by the posterior edge of the condyles. For the tibia, the distal extremity was represented by the center of the joint surface or by the middle of the malleoli; the proximal extremity was represented by the two posterior edges of the tibial plateaux and by the barycenter of the tibial plateaux or the intersection of the diaphyseal axis with the intercondylar tubercle.

Skeletal landmarks: reliability study

A database was created by four different operators. Nine tibias and nine femurs were reconstructed in vivo three times by three operators and twice by a fourth operator. Thus, 99 lower limbs were reconstructed in vivo, including 198 skeletal pieces (99 whole femurs and 99 whole tibias).
Skeletal landmarks for TKR

Figure 3 Construction of the skeletal landmarks. The $\rightarrow Y_{fp}$ and $\rightarrow Y_{tp}$ axes were always oriented upward and are represented by the femoral and tibial mechanical axes, respectively.

The $\rightarrow Z_{fp}$ and $\rightarrow Z_{tp}$ axes were oriented outward for the right knee (inward for the left knee) and directed by the orthogonal projection in the plane perpendicular to $\rightarrow Y_{fp}$ of the epiphyseal segment defining the horizontal plane.

(*) The regional barycenters correspond to the mean of each point of the epiphyseal region involved.

The eight landmarks (four for the femur and four for the tibia) were calculated on all the skeletal reconstructions. The mean landmark corresponding to each skeletal piece was calculated based on the mean of 11 reconstructions from the same knee performed by the four operators. The deviation from the mean of each displacement in rotation and in translation was used to calculate the reliability for each landmark. An automated process was used to export the data into an Excel® file.

Displacement in translation and in rotation

The skeletal landmark of each reconstruction was transferred to the mean landmark using three translations ($T_x$, $T_y$, $T_z$), expressed in millimeters and three successive rotations ($R_x$, $R_y$, $R_z$), expressed in degrees. The three rotation angles, noted $R_x$, $R_y$, $R_z$, characterized the successive rotations of each reconstruction’s skeletal landmark according to the classical sequence of the mobile axis ($x$, $y'$, $z''$), thus measuring the deviations in relation to the mean landmark.

Statistical analysis

Eleven samples were defined for each of the six measurement parameters ($T_x$, $T_y$, $T_z$, $R_x$, $R_y$, $R_z$) and each landmark studied. One sample was made up of the set of the nine values corresponding to the nine knees reconstructed by a single operator. The Friedman test (valid even if the samples did not show a normal distribution) was applied using XLstat® to check whether there was a significant difference between the samples and whether a mean landmark could be calculated. All the samples were kept to calculate the mean landmark for each landmark definition. The normality assumption was verified (Shapiro-Wilk test, $p > 0.05$) for each of the parameters studied. Since certain samples did not show a normal distribution, the distribution of the values was analyzed using box plots and the 95th percentile (rather than the standard deviation). The mean errors, the maximum values, and the 95th percentile corresponding to the 95% confidence interval (95% CI) was calculated for absolute deviations.

Analysis of implant positioning

Analysis of implant positioning based on two cases reconstructed before and after surgery

Two patients underwent total knee arthroplasty at the hôpital Salpêtrière in Paris in May 2006 for femorotibial gonarthrosis and were X-rayed the day before and eight days after surgery. The prosthesis used was the LPS-Flex® model (Zimmer) with a cemented mobile tray, without preserving the posterior cruciate ligament. Bone cuts were made independently with classical centromedullary guides for the femur and extraosseous guides for the tibia. Quadriceps reactivation was sufficient on the eighth day for walking with crutches and standing with no support in the EOS cabin. For both cases, the extension deficit was less than 10° so that the bipedal position could be maintained.

Adjusting the digital 3D implant models and the preoperative 3D skeletal reconstructions to the postoperative EOS knee X-rays

Using the software tool, the preoperative 3D skeletal reconstructions of each of the two patients receiving total knee replacements and the 3D digital models of each corresponding implant were imported into the postoperative 2D EOS® X-rays. Readjusting the prosthesis involved superimposing,
Figure 5  Definition of the angle parameters for implant alignment.
The 3D implant alignment was modeled using the RepFemur4 and RepTibia4 landmarks.
The 3D femoral rotation angle for implantation ($ARot_{Fi,3D}$) was, for the left (right) knee, the 3D angle open outward between $\vec{Z}_{Fp}$ ($\vec{Z}_{Fp}$) and the $\vec{Z}_{Fi}$ ($\vec{Z}_{Fi}$) axis of the femoral piece. The 3D tibial rotation angle for implantation ($ARot_{Ti,3D}$) was the 3D angle between $\vec{X}_{Tp}$ and $\vec{X}_{Ti}$ of the tibial baseplate. If the femoral or tibial rotation angle followed the counterclockwise (clockwise) direction, the value measured was positive (negative). The angles from the 3D goniometry were projected on the anatomical plane that adequately transferred the lower-limb alignment. The projection planes used the skeletal landmarks defined so as to obtain the same angle values, whatever the patient’s position.

(*): 3D angle 3D open inward.

onto the postoperative images, the geometric contours of the 3D digital model of the implanted prosthesis to the radio-opaque edges of the implant. The contours of the pre-operative 3D digital models of each skeletal reconstruction of the femur and the tibia were also superimposed using the software to match the radio-opaque bone edges that were clearly visible on the postoperative EOS® 2D images (Fig. 4).

The 3D implantation angles (Fig. 5) were analyzed using the RepFemur4 and RepTibia4 skeletal landmarks (Fig. 3) and prosthesis landmarks (Fig. 6) positioned in this manner.

Results

Interoperator reliability of the femur and tibia landmarks

Results of femoral landmarks

Translation. Along the longitudinal axis, the mean error, 95% CI, and maximal deviation of $Ty$ remained less than 0.3, 0.5, and 1 mm, respectively (Tables 1 and 2 and Fig. 7). Along the mediolateral and anteroposterior axes, the mean

Table 1  Interoperator reliability of the eight landmarks studied: uncertainty corresponding to the deviations from the mean of the 99 reconstructions.

<table>
<thead>
<tr>
<th>Landmark</th>
<th>Translation (mm)</th>
<th>Interoperator reliability for the femur</th>
<th>Interoperator reliability for the tibia</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$Rx$</td>
<td>$Ry$</td>
<td>$Rz$</td>
</tr>
<tr>
<td></td>
<td>Mean 95% CI Max</td>
<td>Mean 95% CI Max</td>
<td>Mean 95% CI Max</td>
</tr>
<tr>
<td>RepFemur1</td>
<td>0.2 0.5 1</td>
<td>1.2 0.6 20</td>
<td>1.2 0.6 20</td>
</tr>
<tr>
<td>RepFemur2</td>
<td>0.3 0.6 1.5</td>
<td>1.2 0.6 20</td>
<td>1.2 0.6 20</td>
</tr>
<tr>
<td>RepFemur3</td>
<td>0.2 0.5 1</td>
<td>1.2 0.6 20</td>
<td>1.2 0.6 20</td>
</tr>
<tr>
<td>RepFemur4</td>
<td>0.3 0.6 1.5</td>
<td>1.2 0.6 20</td>
<td>1.2 0.6 20</td>
</tr>
<tr>
<td>RepTibia1</td>
<td>0.2 0.5 1</td>
<td>1.2 0.6 20</td>
<td>1.2 0.6 20</td>
</tr>
<tr>
<td>RepTibia2</td>
<td>0.3 0.6 1.5</td>
<td>1.2 0.6 20</td>
<td>1.2 0.6 20</td>
</tr>
<tr>
<td>RepTibia3</td>
<td>0.2 0.5 1</td>
<td>1.2 0.6 20</td>
<td>1.2 0.6 20</td>
</tr>
<tr>
<td>RepTibia4</td>
<td>0.3 0.6 1.5</td>
<td>1.2 0.6 20</td>
<td>1.2 0.6 20</td>
</tr>
</tbody>
</table>
| 95% CI; uncertainty estimated by the 95% confidence interval; Max: maximum error for each variable.
Skeletal landmarks for TKR

Table 2

<table>
<thead>
<tr>
<th>Interoperator reliability of the eight landmarks studied: uncertainty corresponding to the deviations from the mean of the 99 reconstructions.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rotation (°)</strong></td>
</tr>
<tr>
<td><strong>Mean</strong></td>
</tr>
<tr>
<td>RepFemur1</td>
</tr>
<tr>
<td>RepFemur2</td>
</tr>
<tr>
<td>RepFemur3</td>
</tr>
<tr>
<td>RepFemur4</td>
</tr>
<tr>
<td><strong>95% CI:</strong> uncertainty estimated by the 95% confidence interval; Max: maximum error for each variable.</td>
</tr>
</tbody>
</table>

![Figure 6](image)

**Figure 6** Landmarks that defined the tibial baseplate and the left femoral component.

Landmark related to the femoral component:
- the vector $\vec{Z}_{Fi}$ (Fi: femur, implant) supported the line joining the summit of the two anchoring studs and was oriented from outside to inside (inside to outside) for a left (right) implant;
- directed upward, the vector $\vec{Y}_{Fi}$ was parallel to the anchoring studs and perpendicular to the distal box of the femoral implant;
- vectorial product of $\vec{Y}_{Fi}$ and $\vec{Z}_{Fi}$, the vector $\vec{X}_{Fi}$ was perpendicular to the anchoring studs and directed forward;

Landmark related to the tibial baseplate:
- the vector $\vec{Y}_{Ti}$ (Ti: tibia, implant) was perpendicular to the plateau plane of the tibial baseplate and directed upward;
- The vector $\vec{Z}_{Ti}$ was parallel to the posterior biglenoid edge of the tibial implant, oriented from outside to inside (inside to outside) for a left (right) implant.

Located in the plane of the tibial implant’s sagittal symmetry, the vector $\vec{X}_{Ti}$, vectorial product of $\vec{Y}_{Ti}$ and $\vec{Z}_{Ti}$, was parallel to the plateau plane and directed forward.

Rotation. For the rotations around the mediolateral and anteroposterior axis, the mean error, 95% CI, and maximal deviation remained less than 0.2, 0.5, and 0.8°, respectively. For the RepFemur2 and RepFemur4 landmarks, the mean error, 95% CI, and the maximal deviation of $Ry$ remained less than 0.8, 2.9, and 6°, respectively (versus 1.3, 5.1, and 8.1° for RepFemur1).

Results of tibial landmarks

Translation. The absolute value of the deviation from the mean for the translations along the longitudinal axis of the tibia remained below 1 mm for the RepTibia2, RepTibia3, and RepTibia4 landmarks, with 95% of the Ty values less than 0.6 mm. The translations along the mediolateral axis remained under 1.7 mm for the same landmarks, with 95% of the Tz less than 0.6 mm. A maximum of 3.4 mm was
For each variable of the RepTibia4 (a) and RepFémur4 (b) landmarks, box plots analyzing the distribution of the deviations from the mean of the 99 reconstructions. The maximum values and means of each parameter are expressed at the summit and the right of the corresponding box plot, respectively.

reached for the anteroposterior translations, with 95% of the Tx values less than 1.4 mm. For the Tz variable of RepTibia1, the mean deviation, 95% CI, and the maximal deviation reached 0.8, 2.3, and 5 mm, respectively.

Rotation around the longitudinal axis. For Ry, the mean deviation, 95% CI, and the maximal deviation reached 4.1, 11.2, and 19.9°, respectively for all the landmarks.

Rotations around the anteroposterior and mediolateral axes. For all the tibial landmarks, the mean deviation, 95% CI, and the maximal deviation of Rx remained less than 0.2, 0.5, and 1.1°, respectively. For the RepTibia1 and RepTibia2 landmarks, the mean deviation, 95% CI, and the maximal deviation of Rz remained less than 0.2, 0.6, and 1°, respectively. For the RepTibia3 and RepTibia4 landmarks, these values reached 0.4, 1.3, and 1.6°, respectively.

3D angles measured

The femorotibial mechanical angle reflecting the alignment of the lower limb was 181.2° and 179.2° for patients 1 and 2, respectively (Table 3 and Fig. 8). The femoral mechanical angle was 93.9° and 92.4°. The tibial mechanical angle was 87.3° and 85.6°. For patient 1, the sum of the femoral mechanical angle (93.9°) and tibial angle (87.3°) was equal to the femorotibial mechanical angle (181.2°), demonstrating an absence of frontal ligament laxity in the upright position. Tibial slope was 81.5° and 86.2°, a respective deviation of −1.5° and 3.2° compared to the 83° tibial slope recommended by the manufacturer. In relation to the posterior bicondylar line, the rotation of the femoral component was 9.3° and 4.1°, for a 6.3° and 1.1° deviation in external rotation compared to the 3° planned. The tibial baseplate was positioned in 10.7° external rotation for patient 1 and in 4.7° internal rotation for patient 2.

Discussion

Patient position and angle measurement precision

Frontal knee geometry measurement while standing on both feet [6,10,18–21] is the gold standard radiographic examination to measure lower limb alignment. The various standardization protocols used in conventional goniometry (feet together, patellae facing forward, lateral condyle

Figure 7 For each variable of the RepTibia4 (a) and RepFémur4 (b) landmarks, box plots analyzing the distribution of the deviations from the mean of the 99 reconstructions. The maximum values and means of each parameter are expressed at the summit and the right of the corresponding box plot, respectively.

Table 3 3D implantation angles projected in the appropriate planes and expressed in degrees for the two patients studied.

<table>
<thead>
<tr>
<th>Angle</th>
<th>Patient 1</th>
<th>Patient 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical femoral angle</td>
<td>93.9</td>
<td>92.4</td>
</tr>
<tr>
<td>Femoral slope</td>
<td>85.2</td>
<td>86.2</td>
</tr>
<tr>
<td>Femoral rotation</td>
<td>9.3</td>
<td>4.1</td>
</tr>
<tr>
<td>Mechanical tibial angle</td>
<td>87.3</td>
<td>85.6</td>
</tr>
<tr>
<td>Tibial slope</td>
<td>81.5</td>
<td>85.4</td>
</tr>
<tr>
<td>Tibial rotation</td>
<td>10.7</td>
<td>−4.7</td>
</tr>
<tr>
<td>Mechanical femorotibial angle</td>
<td>181.2</td>
<td>179.2</td>
</tr>
</tbody>
</table>

For the rotations, the values were positive (negative) if the 3D angle followed the counterclockwise (clockwise) direction.

Figure 8 EOS® 3D positioning of patient 1’s femoral implant showing the rotational adjustment with the femoral skeleton. The landmarks attached to each 3D model allow measurement of the 3D angles in the calibrated environment of the EOS® system.
Skeletal landmarks for TKR

of the diaphyseal inertia axis is by definition highly reliable. Inferior results on translation be explained? The calculation marks, the T-condylar sphere. For the RepFemur1 and RepFemur3 landmarks, which start from the middle of the segment joining the center of each posterior condyles for the femur, and the anterior tibial tuberosity and edge of the lateral condyle, the trochlear groove, the epicondyles for the femur, and the anterior tibial tuberosity and the intercondylar tubercle surface for the tibia. These data are important in defining clinically relevant landmarks that remain robust, that is, hardly influenced by the uncertainties of reconstruction. Do the reconstructed models retain the same precision when the bone contours are deformed by osteophytes or are superimposed at the back of a bone depression? Bauer [25] conducted a preliminary study on the precision of reconstruction using conventional stereography of four knees with osteoarthritis in reference to CT. The mean error varied for distal femur (distal tibia) reconstructions by 0.9 to 1.2 mm (1.2—1.6 mm), with a maximal error of 7 mm (7.3 mm). These results are encouraging, but this in vivo study was not conducted on entirely reconstructed tibias and femurs. The diaphyses often have a combined incurvation in the sagittal and frontal planes that must be taken into account by the reconstruction algorithms. A precision study needs to be conducted with a greater number of osteoarthritic lower limbs that have been entirely reconstructed.

Choice and precision of the landmarks used

Results of femoral landmarks

Translation. Reliability in translation was better for the RepFemur2 and RepFemur4 landmarks, which start from the middle of the segment joining the center of each posterior condylar sphere. For the RepFemur1 and RepFemur3 landmarks, the Tx and Ty values nearly tripled. How can these inferior results on translation be explained? The calculation of the diaphyseal inertia axis is by definition highly reliable. The trochlear surface where the diaphyseal axis is projected has already been identified; however, as an anatomical zone with less precision [17]. The line of the trochlear groove can easily be identified on the lateral views, but the reconstruction of its surface can be negatively influenced by the anterior condylar contours that are sometimes less visible. Rotation. For the rotations around the mediolateral and anteroposterior axes, reliability was good for all the femoral landmarks. For the rotation around the longitudinal axis, the landmarks using the posterior edge of the condyles and the center of the posterior condylar spheres to define the mediolateral axis were less reliable. The posterior condyles have the advantage of having radiographic contours that can always be clearly discerned and are not deformed by arthritic wear. So as not to confuse the medial and lateral condyle, the operator navigates simultaneously on two radiographic views using the software. The posterior edge of the medial condyle is located on the lateral image level with the medial plateau, which can easily be identified by its abrupt posterior rim. In addition, the condyle has an indentation in front, level with the roof of the notch, presenting an angular contour at the back.

Results of tibial landmarks

Translation. The reliability of the tibial landmarks was very good in translation using the barycenter of the tibial plateaux to define the starting point. The projection of the proximal diaphyseal axis on the anterior intercondylar surface was less reliable. The intercondylar tubercle has already been recognized as an anatomical zone of imprecision [13].

Rotation around the longitudinal axis. The imprecision of the nodes located at the posterior edge of the two plateaux [17] probably affected the reliability of positioning the tibia’s skeletal z-axis. The large 11.2° deviation for Ry reflected the imprecision of the construction of the mediolateral z-axis, which essentially had repercussions on the analysis of the tibial baseplate. The precision of the two anatomical points that construct the z-axis actually depend on the radiographic contours of the tibial plateau being clearly visualized. Standardization of the above-described EOS® X-ray exam and the ongoing improvement of the reconstruction techniques should optimize these results by preventing reconstruction errors secondary to skeletal superimpositions on the lateral images. Rotations around the anteroposterior and mediolateral axes. The small deviations between Rx and Rz show that the tibial mechanical axis used for the tibial mechanical angle measurements and the implant’s tibial slope were highly reliable. In sum, all of the tibial landmarks had a reliability comparable to the rotations, which were precise around the anteroposterior and mediolateral axes.

The advantages of using the RepFem4 and RepTib4 landmarks

The RepFem4 and RepTib4 skeletal landmarks presented the least uncertainty and were similar to those used in computer-assisted surgery. Therefore, validating these landmarks is important in analyzing implant position. The epiphyseal surface points participating in the construction of the mechanical axis of the RepFem4 and RepTibia4 land-
marks correspond to the points where the centromedullary guides used in orthopedic surgery of the knee are introduced. The 3D orientation of the femur and tibia bone cuts is therefore determined based on these truly pivot points that participate in the construction of the mechanical axes. The posterior bicondylar line is a vital anatomical landmark used in conventional or computer-assisted prosthetic surgery to properly position the femoral component in rotation. One may wonder why the anterior tibial tuberosity has not been used to construct the tibial landmarks. Certain navigation systems [3] require the operator to make an acquisition of the anteroposterior X vector to define the reference sagittal plane with the mechanical axis; a navigation pointer is positioned parallel to the tibial plateau between the two intercondylar tubercles at the base of the anterior tibial tuberosity. The frontal EOS® X-ray does not allow proper visualization of the anterior tibial tuberosity advancement, even though it remains a vital landmark during surgery to analyze the position of the tibial baseplate in rotation. The center of the ankle is often defined using the two malleoli in reference to the navigation systems and the extramedullary tibial guides. Siston et al. [26] showed that the most medial point of the medial malleolus and the most lateral point of the lateral malleolus were precise anatomic references in computer-assisted surgery to define the center of the ankle.

3D analysis of implant positioning

In a 3D environment, the EOS® X-rays make it possible to clearly draw the anatomical and mechanical axes required for the analysis of implant position. However, the construction of skeletal landmarks requires the acquisition of pre- and postoperative images, with the bone cuts required for implantation removing a part of the posterior femoral condyles and all of the posterior edges of the two tibial plateaux. The epicondyles and the anterior tibial tuberosity could be used to define the skeletal landmarks after implantation, but these zones are not reconstructed with sufficient precision in the EOS® system to constitute a reliable Z vector in the horizontal plane. Reconstructing a preoperative model allows one to define a mechanical axis that is not related to the implants, contrary to the classic 2D angle measurements. To evaluate the reliability of the implant adjustment on the X-rays, Nodé-Langlois [17] measured femoral and tibial mechanical implantation angles of prostheses of ten patients after having superimposed the 3D model contours of the femoral component and the tibial baseplate on the X-ray contours of these implants. The mean error in the reliability of the prosthesis adjustment remained less than 1°, with a maximal error of 1.1°. The software readjustment technique developed by the Paris Biomechanics Laboratory, ENSAM, is therefore reliable. In addition, the skeletal models reconstructed pre- and postoperatively should be sufficiently precise and close to the patient’s anatomical model to superimpose all their contours perfectly on the postoperative X-rays. Of the two cases that we measured, only the epiphyses of the knee required to put in place the landmarks were readjusted on the postoperative X-rays. The angle measurements obtained in the frontal and sagittal planes were credible and comparable to those from the 2D angle measurements. In the horizontal plane, the postoperative CT scan could not be used for baseline calculations because the rotation measurements used anatomical zones that had been removed. These preliminary results are encouraging, although the measurement protocol now needs to be validated on a larger series of patients.

Future perspectives

Positioning 3D implant models adapted in size to the preoperative EOS® X-rays can make true 3D planning of the baseline position chosen possible. Alignment of the lower limb with its implant [4] should aim for 180° ± 3° and each component of the prosthesis should be aligned to 90° ± 2° compared to the mechanical axis. The planned implant position could then be compared to the position actually obtained.

Use of similar landmarks for navigation as well as pre- and postoperative EOS® evaluation will make it possible to achieve true comparisons of the results of the different steps. TKA patient follow-up will consist of repositioning the implant models used and the skeleton reconstructed before surgery on the follow-up EOS® images.

Conclusion

The precision of the landmarks defined is directly related to the quality of the corresponding skeletal reconstructions. Certain errors can be avoided by positioning the patient properly in the EOS® cabin and by the proper use of the software and good knowledge of the radiological contours of the knee on the part of the operators. Improving the robustness of the reconstruction algorithms should contribute better precision to certain anatomical zones. The low dose of irradiation received by the patients and the realistic loaded mechanical conditions make EOS® stereoradiography a tool of the future for the follow-up of TKA patients.

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References

Skeletal landmarks for TKR


