Femoral shaft bowing in valgus knees
An anatomic study

Incurvation frontale de la diaphyse fémorale du genu valgum constitutionnel : étude anatomique

J. Brilhault *, C. Ledu *, J.-J. Rousselle **, P. Burdin *

* Service de Chirurgie Orthopédique et Traumatologique 1, Hôpital Trousseau, CHRU de Tours, 37044 Tours Cedex.
** Laboratoire d’Informatique (EA 2101) de l’École Polytechnique de l’Université de Tours, 64, avenue Jean-Portalís, 37200 Tours.

RÉSUMÉ
Lors d’une précédente étude anatomique sur genoux sains, nous avions observé que le valgus fémoral ne pouvait être attribué à une hypoplasie du condyle fémoral latéral. Nous avons donc repris le même échantillon pour analyser la morphologie des diaphyses fémorales.

Il s’agissait d’une étude cadavérique portant sur 41 membres inférieurs sains de sujets caucasiens âgés de plus de 65 ans. Trois paramètres angulaires étaient analysés : l’axe mécanique du membre (HKA), le valgus fémoral mécanique (HKI) et le valgus fémoral anatomique (SKI). Il y avait 23 genoux normaux (HKA : 179,1° ± 1,6) et 18 genu valgum (HKA : 182,7° ± 0,8). La morphologie de la diaphyse fémorale était analysée par squeletisation puis modélisée par une fonction du deuxième degré \( y = f(x^2 + bx + c) \). L’angle HKI des genu valgum (95,5° ± 1,1) était supérieur à celui des genoux normo-axés (93,6° ± 2,4) ce qui confirmait l’origine fémorale du valgus. Le paramètre de forme \( f \) des genoux normo-axés (1,33 \times 10^{-5} ± 1,41 \times 10^{-5}) était supérieur à celui des genu valgum (5,71 \times 10^{-6} ± 5,27 \times 10^{-6}). Une corrélation était observée entre le paramètre de forme \( f \) et l’angle HKI dans le groupe des genu valgum.

L’analyse des données nous a permis d’attribuer au segment diaphysaire du fémur une part importante dans la déformation du genu valgum constitutionnel. Nous formulons l’hypothèse qu’il en est de même en cas de gonarthrose sur genu valgum constitutionnel.

Mots clés : Anatomie, fémur, diaphyse, genu valgum.

ABSTRACT

Purpose of the study
In a previous anatomic study of healthy knees, we observed that femoral valgus cannot be attributed to hypoplasia of the lateral femoral condyle. In the present study, in an attempt to determine the site of the femoral deformation, we examined femoral shaft bowing in the frontal plane.

Material and methods
This cadaver study included 41 lower limbs of healthy Caucasian subjects aged over 65 years. The following anatomic landmarks were identified: center of the femoral head (H), center of the intercondylar notch (K), center of the talar dome (A), center of the femoral shaft half way between the apex of the greater trochanter and the middle of the intercondylar notch (S), and the tangent line of the femoral condyles (I). Three angles were analyzed: HKA, HKI, and SKI. There were 23 normal knees (HKA = 179,1° ± 1,6) and 18 valgus knees (HKA = 182,7° ± 0,8). Skeletal analysis (the skeleton of an object being defined as the median points of the object) was used to describe the morphology of the femoral shaft and then to model it with a second-degree function \( y = f(x^2 + bx + c) \). The protocol was repeated seven times to achieve accurate measurement. Accuracy was 1° for the HKA angle and 0.45° for the HKI and SKI angles. This accuracy was comparable to that reported in the literature. The Mann-Whitney U test was used to compare means. Spearman’s \( r \) test was used to search for correlations. The first-order risk was set at 0.05.
Results

The HKI angle for valgus knees (95.5 ± 1.1°) was greater than for the normally aligned knees (93.6 ± 2.4°), confirming the femoral origin of the valgus. The form parameter f for the normal knees (1.33 ± 1.41) was greater than for the valgus knees (5.71 ± 5.27). There was a correlation between the form parameter f and the HKI angle for valgus knees, reflecting a relationship between frontal bowing of the femoral shaft and femoral valgus in this group.

Discussion

The difference observed between the two groups of knees regarding the form parameter f and the correlation between f and the HKI angle in the valgus knees led us to consider that a considerable proportion of constitutional valgus knees can be attributed to the femoral shaft. Thus for equivalent anatomic valgus (SKI), minimal bowing (f) of the femoral shaft in valgus knees leads to greater mechanical valgus (HKI). These results confirm those obtained in our earlier study, where we concluded that hypoplasia of the lateral femoral condyle does not contribute to constitutional valgus knees. We hypothesize that the same could be true for degenerative disease of constitutional valgus knees. For surgical cure, the origin of the misalignment in valgus knees dictates the rotation position of the femoral component of total knee arthroplasty and the lengthening technique for the lateral structures.

Key words: Anatomy, femur, diaphysis, valgus knee.

INTRODUCTION

Valgus knees are classically attributed to a misalignment of the distal extremity of the femur [Keblish (1), Krackow et al. (2)], Whiteside and Arima (3), Aglietti et al. (4)]. In an earlier study on osteoarthritis-free knees, we observed that femoral valgus could not be attributed to hypoplasia of the lateral femoral condyle [Brilhault et al. (5)]. Seeking to localize the misalignment site in valgus femur, we investigated its diaphysis morphology in a study on the same sample to see if there was a correlation, in the frontal plane, between mechanical femoral valgus and femoral shaft bowing.

MATERIAL AND METHODS

This cadaver study included 41 lower limbs of healthy (with no osteoarthritis, tumor, fracture, or surgery) Caucasian subjects aged over 65 years. The limbs were disarticulated at the hip and were placed in full extension on their posterior side. An anterior longitudinal incision was made at the hip and were placed in full extension on their posterior side. An anterior longitudinal incision was made to look for the presence of osteoarticular pathology and to view the femoral head, the knee, and the ankle. The center of the hip (H) was equated with the center of the femoral head identified by Moose’s circle. The center of the knee (K) was equated with the center of the intercondylar eminence. The center of the ankle (A) was equated with the center of the talar dome. The joint centers were materialized by pins and the mechanical axes by strings extended between them. The HKA angle was measured on the medial side of the knee using a goniometer, between the mechanical axis of the femur and the tibia, which had already been marked. Each measurement was taken three times and the median was noted (accuracy was evaluated at 0.45°).

To define two groups of knees, we referred to the study by Hsu et al. (6) investigating 120 knees with no pathology. This study concluded on a mean HKA angle of 178.8° ± 2.2°. We thus classified the limbs studied into two groups according to HKA angle: normal knees (176.6° ≤ HKA ≤ 181°) and valgus knees (HKA > 181°). From this first stage, 41 lower limbs were included in the study, with 14 bilateral cases. There were 23 normal knees (HKA = 179.1° ± 1.6; median 180°; range, 177°-181°) and 18 valgus knees (HKA = 182.7° ± 0.8; median, 183°; range, 182°-184°).

Femurs were then removed, respecting the articular cartilage. Each femur was photographed lying on the posterior edges of the condyles and the greater trochanter. These three points defined the frontal plane. Use of a camera arm (Kaiser®, RTX, Germany) allowed us to take photos parallel to the frontal plane at a constant distance (112 cm). Each photo was digitized and the angle measures were produced by a single operator directly on the images enlarged ten times using drawing software (Corel Draw 7°).

We retained the angle parameters that are classically used during preoperative planning for total knee replacement [Chatain (7)] (fig. 1). Line I was the tangent line of the femoral condyles. Point K was located at the center of the intercondylar notch, the presumed location of the center of the intercondylar eminence. Point S was located at the center of the femoral shaft half way between the apex of the greater trochanter and the middle of the intercondylar notch [Moreland et al. (8)]. Angle HKI quantified the mechanical femoral valgus. Angle SKI measured the anatomical femoral valgus. As in the earlier measurements, each of these measurement was repeated three times and the median was retained (accuracy was evaluated at 0.45°).

The search for a mathematic description of frontal bowing of the femoral shaft required the use of image analysis techniques. The graphic representations of the different steps are illustrated in fig. 2. Skeletal analysis was used as the main means, an operation that describes an object through a set of lines (analogous to the structure of the object), thus reducing the volume of information to process. The skeleton of an object is defined as the median points of the object, the object analyzed corresponding to the femoral diaphysis. It was manually delimited proximally by the distal edge of the lesser trochanter and distally by the adductor
FEMORAL SHAFT BOWING IN VALGUS KNEES

magnus muscle. Once the skeletal analysis was completed, we obtained a simple curve to analyze. This curve was analyzed with a second-degree function \( y = fx^2 + bx + c \) using Matlab® software. The \( f \) parameter was a form parameter proportional to the radius of the femoral shaft’s mean curve. We retained this parameter to quantify the frontal bowing of the femoral shafts studied.

When the research protocol was being designed, the precision of the measurements taken was evaluated by repeating the protocol seven times on a single femur and by calculating the absolute uncertainty for each angle measured (the precision of an experimental result whose domain of probable values falls between \( x_{\text{max}} \) and \( x_{\text{min}} \) can be expressed by absolute uncertainty \( \Delta x = (x_{\text{max}} - x_{\text{min}})/2 \)). The absolute uncertainty of the measurement of the HKA angle was 1.0°. The absolute uncertainty of HKI and SKI angle measurements was 0.45°. This precision, assessed using an identical method, was comparable to that obtained by Yoshioka et al. (9), whose work we took as a reference.

Although in 14 cases both limbs of the same body were included, we postulated that the limbs observed were independent and we chose to analyze them as such. This choice is explained in the Discussion. The choice of the statistical tests was imposed by the small sample size in each group; these analyses were done with StatView 4.47 software (Abacus Concepts, Inc.©). We used the Mann-Whitney U test to compare the means observed. Correlations were calculated using the Spearman \( t \) test. Bilateral tests were used: the null hypothesis (H0) was defined as no difference or no correlation between the groups. The first-order risk \( \alpha \) was set at 0.05.

RESULTS

The means and their comparisons are reported in table I. The HKI angle of the valgus knees (95.5° ± 1.1°) was higher than the same angle for normally aligned knees (93.6° ± 2.4°). The form parameter \( f \) of the normally aligned knees (1.33 10^-5 ± 1.41 10^-5) was higher than that of the valgus knees (5.71 10^-6 ± 5.27 10^-6). The femurs of the normal knees therefore presented greater shaft bowing than the valgus knees, which can be viewed in figs. 3 and 4. The different parameters studied were correlated on all knees, then separately in the two subgroups. These are reported in tables II, III, and IV.

DISCUSSION

The difference observed between the two groups of knees concerned parameter \( f \) as well as the correlation between this parameter and the HKI angle in the valgus knee group; we attributed a high proportion of the constitutional knee valgus to the diaphyseal segment of the femur. Indeed:

- the HKI angle of the valgus knees was higher than that of normally aligned knees and the HKA angle correlated with the HKI angle, confirming the femoral origin of the valgus;

![FIG. 1. – Graphic illustration of HKI and SKI angles.](image1)

![FIG. 2. – Graphic illustration of skeletal analysis of the diaphysis. a) Digitized image of the femur. b) Skeleton of the femoral shaft (bold). The arrows indicate the diaphyseal region.](image2)
• the HKI angle was correlated with the SKI angle, demonstrating the relation between mechanical femoral valgus and anatomic femoral valgus;
• the parameter form $f$ of normally aligned knees was higher than that of valgus knees, demonstrating a different diaphyseal bowing between the two groups;
• the correlation observed between the parameter form $f$ and the HKI angle in the valgus knee group demonstrated that there did indeed exist a relation between the femoral shaft and the femoral valgus of the valgus knee.

Thus, at identical anatomic valgus (SKI), the low frontal bowing ($f$) of the femoral shafts of valgus knees leads to a higher mechanical valgus (HKI) (fig. 3). Although several studies underscore the variations in the shape of the femoral shaft [Hsu et al. (6), Oswald et al. (10), Merckx et al. (11)], only Moreland et al. (8), in a radiographic study of healthy knees, concluded in a supracondylar origin for femoral valgus. These results confirm those of our previous study in which we concluded that there was no hypoplasia of the femoral condyle and that valgus knee did not originate in the femoral shaft in constitutional valgus knees [Brilhault et al. (5)]. The presence of frontal femoral shaft bowing ($f$) that was different in the two groups, even though the anatomic valgus (SKI) was similar, implies that the proximal half of the femur is involved in the femor’s mechanical axis. This proximal component of the misalignment can be attributed to several factors [Thomine et al. (12)]; the frontal bowing of the proximal half of the femoral shaft, the length of the femoral neck, and its orientation. This study is limited in that it did not study these parameters. As a source of variations, they probably partly explain the lack of correlation observed between the parameter form $f$ and the HKI angle in the group of normally aligned knees.

The limits of this study reside mainly in its methodological shortcomings, detailed below:
• the sample observed was made up of knees without osteoarthritis presenting small misalignments. The valgus knees that gave rise to osteoarthritis perhaps result from a morphology that is different from the morphology we observed;
• separating valgus knees and aligned knees may seem artificial given the small misalignments. However, substantial misalignments encountered in pathology would probably have presented osteoarthritis of the knee, osteotomy antecedents (even both), which would have resulted in unreliable measurements;
• in 14 cases, both limbs of the same body were included and analyzed as independent. Since the constitutional valgus knee was usually bilateral, our choice should be explained. Excluding the 27 contralateral limbs was related to modifications in the natural anatomy of these subjects (fracture or surgery, mainly hip arthroplasty). The distribu-

### Table I. – Comparison of means between valgus and normal knees.

<table>
<thead>
<tr>
<th></th>
<th>Total</th>
<th>Valgus knees</th>
<th>Normal knees</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>41</td>
<td>18</td>
<td>23</td>
<td>—</td>
</tr>
<tr>
<td>HKA angle</td>
<td>180.7 ± 2.2</td>
<td>182.7 ± 0.85</td>
<td>179.2 ± 1.55</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>HKI angle</td>
<td>94.4 ± 2.1</td>
<td>95.5 ± 1.1</td>
<td>93.6 ± 2.4</td>
<td>0.015</td>
</tr>
<tr>
<td>SKI angle</td>
<td>99.4 ± 1.7</td>
<td>99.9 ± 1.2</td>
<td>99.0 ± 1.9</td>
<td>0.088</td>
</tr>
<tr>
<td>$f$</td>
<td>$1.02 \times 10^{-5}$</td>
<td>$5.71 \times 10^{-6}$ ± $5.27 \times 10^{-6}$</td>
<td>$1.33 \times 10^{-5}$ ± $1.14 \times 10^{-5}$</td>
<td>0.042</td>
</tr>
</tbody>
</table>

Mean and standard deviation. Angles are expressed in degrees. $P$-values express comparisons of means between valgus knees and normal knees.

![Fig. 3. – Graphic illustration of morphological differences (diaphyseal curve and HKI angle) between the femur of the valgus knee (dotted line) and the femur of the normally aligned knee (in gray).](image)
tion of the limbs presented no differences whether or not they belonged to the same body (table V) and the literature reports no difference in HKA angle related to sex or side [Hsu et al. (6), Glimet et al. (13, 14)]. We therefore postulated that the limbs studied were independent and we chose to analyze them as such:

• the lack of an interobserver study stems from a single observer taking all the measurements. The precision of the measurements taken was comparable to that reported in a similar morphometric study that we used as a reference [Yoshioka et al. (9)]. We deemed this precision, greater than the anatomic variations observed, adequate to pursue the morphometric analysis. Consequently, we did not attempt to increase the number of observers;

• the lack of a correlation between HKA and HKI angles observed separately in the two groups was attributed to insufficient statistical power of the test related to the low sample size in each group since it was found in the analysis of all the knees;

• finally, the lack of three-dimensional tomodensitometric measurements meant we could not integrate the bone torsion component into our analysis [Duparc et al. (15), Burgaud (16)].

Subject to the applicability in pathology of our observations, several surgical uses can be garnered from this study. If the hypothesis of an extra-articular cause of constitutional valgus knee is retained, the form of the distal femoral shaft should be considered normal (no hypoplasia for the lateral femoral condyle). Constitutional misalignment should be corrected in the frontal plane (knee in extension), during placement of a knee implant. It is possible to correct the valgus in an isolated fashion with supra-condylar osteotomy and then to proceed to full knee replacement within its ligaments, as for a normally

<table>
<thead>
<tr>
<th>HKA angle</th>
<th>HKI angle</th>
<th>SKI angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>HKI angle</td>
<td>0.620</td>
<td></td>
</tr>
<tr>
<td>SKI angle</td>
<td>0.359</td>
<td>0.657</td>
</tr>
<tr>
<td>f</td>
<td>0.416</td>
<td>0.555</td>
</tr>
</tbody>
</table>

Significant correlations are in bold.
aligned limb. It is also possible to correct the valgus in cross-sections of bones. The cross-section of the distal femur is perpendicular to the mechanical axis of the limb calculated on the preoperative x-ray of the knee. The lateral formations should therefore only be laid out in knee extension. This idea has been retained in our practice [Brilhault et al. (17)]. In addition, when there is no hypoplasia of the lateral femoral condyle, there is no reason to increase the lateral rotation of the femoral component of total knee implants based on constitutional valgus knee; the posterior condylar reference can be used. Finally, this study underscores the anatomic variations of the femoral diaphysis. In clinical practice, these variations are best viewed on knee x-rays [McGrory et al. (18)], which provide precise measurement of the angle formed by the mechanical axis of the femur and the medullary canal [Oswald et al. (10)]. Nevertheless, other parameters intervene in the precision and reproducibility of the bone cross-sections taken using guides with intramedullary pins; the main ones being the distal entry point of the pin, the length of the pin, its diameter, and the width of the femoral intramedullary cavity [Teter et al. (19), Reed and Gollish (20), Nuno-Siebrecht et al. (21)]. Consequently, using navigation seems an obvious solution for accurate and reproducible femoral cross-sections.

References


TABLE IV. – Correlation coefficient ρ of the Spearman test carried out on normally aligned knees.

<table>
<thead>
<tr>
<th></th>
<th>HKA angle</th>
<th>HKI angle</th>
<th>SKI angle</th>
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<tbody>
<tr>
<td>HKI angle</td>
<td>0.353</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SKI angle</td>
<td>0.237</td>
<td>0.795</td>
<td></td>
</tr>
<tr>
<td>f</td>
<td>0.418</td>
<td>0.433</td>
<td>0.349</td>
</tr>
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Significant correlations are in bold.

TABLE V. – Distribution of knees according to whether they were part of the same cadaver (bilateral or unilateral).

<table>
<thead>
<tr>
<th></th>
<th>Valgus knees</th>
<th>Normal knees</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bilateral</td>
<td>8</td>
<td>6</td>
<td>14</td>
</tr>
<tr>
<td>Unilateral</td>
<td>10</td>
<td>17</td>
<td>27</td>
</tr>
</tbody>
</table>

The distribution difference measured using the chi square test is nonsignificant (p = 0.8070).

