Tibial Anatomy and Functional Axes

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Summary: Articular geometry of the tibia has been studied in relation to the functional axis and extra-articular bone landmarks, using a Cartesian coordinate system. Thirty-one cadaver limbs were used, 26 of them paired. The donor age range was 61 to 89 years (17 females, 14 males), none of whom showed evidence of significant arthritic deterioration. Most linear parameters were greater in males than females (p < 0.005), and correlations between these parameters were noted, e.g., tibial length versus plateau width (r = 0.7, p < 0.01) with both genders combined. Gender differences occurred in only two of the angular parameters—tibial torsion (p < 0.025) and foot rotation (p < 0.005). For the latter, mean rotation was internal (-5°) for males, and external (11°) for females. No correlations between angular parameters were found. In the paired limbs, there was asymmetrical distribution of just two parameters—varus tilt of the tibial plateau margins (p < 0.005) and lateral deviation of the tuberosity (p < 0.025). The data complement a previous report on the femur. These studies are relevant to the kinematics of the lower limb, design and sizing of resurfacing components, and possibly to the pathogenesis of osteoarthritis. Key Words: Tibia—Geometry—Anatomy—Osteoarthritis.

There are many descriptions of lower leg bone dimensions derived from clinical examinations (7,11,15) and roentgenograms (1,4,5,15). Measurements of radiographic features in vivo have some disadvantages when compared with direct measurements on cadaver bones, due to difficulties in defining the rotational position of the limb and/or alignment of the bones. Furthermore, roentgenographic outlines of joints do not define the cartilaginous outlines of the articular surfaces.

Our particular interest has been to define relationships of articular geometry to the functional mechanical axes of the lower limb. Having recently described the anatomy and functional axes of the femur (16), we have extended our studies to the tibia, specifically to define the morphology of the proximal articular surfaces in relation to the functional axes and elements of tibial rotation and alignment of the foot. The data obtained may be useful in optimizing design, sizing, and positioning of tibial implants, as well as in our understanding of limb alignment.

MATERIALS AND METHODS

Source of Samples and Methods of Measurement

We used 31 intact, embalmed Caucasian cadaveric lower legs (26 of them paired) from the Department of Anatomy, Queen's University. Age range of the donors was 61 to 89 years, 17 of whom were female. Soft tissues, including joint capsule and ligaments, were dissected from the tibia and fibula and the knee was disarticulated. Limbs featuring gross tissue changes, consistent with significant arthritic deterioration, were excluded from the study.
A small pin was inserted to mark the center of the tibial plateau (midinterspinous point), and two marker points were placed into the dorsal aspect of the second toe metatarsal (the second ray line). Photographs, at a distance of 3 m, were taken from the proximal tibial perspective, along the axis of the bone (Fig. 1A). The ankle was then disarticulated, leaving the proximal and distal tibiofibular joints intact. The knee center at the tibial plateau (O) was located and marked at the midpoint of a line (S1S2) drawn between the medial and lateral intercondylar eminences (Fig. 2A). The center of the ankle (C) was defined as the intersection point of two diagonals drawn from the corners of the weight-bearing area of the distal articular surface (Fig. 2B). The long axis of the tibia (which may also be viewed as the functional axis) was then located as a line passing through the center of the knee to the center of the ankle (15). The tibia was then located by two supports on an osteometric table containing scales corresponding to X, Y, and Z coordinates (Fig. 3). The tibia was first positioned with the long axis parallel to the Y scale, and was then aligned in the transverse plane by rotating it to bring the transverse axis of the tibial plateau (defined below) parallel to the Z scale. This procedure allowed for subsequent location of various bone landmarks in relation to the Cartesian coordinates, with measurements in the different cadaveric limbs all standardized with respect to the tibial axis and "neutral" rotation of the knee. The method was calibrated by taking seven linear measurements on a single specimen, and repeating each one six times. Standard deviations of less than 0.7 mm were obtained, which were less than 2% of the mean value for the smallest linear measurement.

**Geometric Constructions and Parameters Measured**

The anterior border of the tibial plateau (AB) is a line drawn tangentially to (and joining) the anterior margins of the medial (A) and lateral (B) articular surfaces of the tibial plateau (Fig. 1A and B).

The posterior border of the tibial plateau (GH) is a line drawn tangentially to (and joining) the posterior margins of the medial (G) and lateral (H) articular surfaces of the tibial plateau (Fig. 1B).

The transverse axis of the tibial plateau (Tr) is a line through the knee center (O), parallel to AB in the transverse plane (Fig. 1B). In the frontal plane,
FIG. 3. Osteometric table with the tibia in position. The long axis is parallel to the Y scale, and the transverse axis of the tibial plateau is parallel to the Z scale.

Tr is perpendicular to the long axis of the tibia (Fig. 4A).

The anterior/posterior axis of the tibial plateau (AP) is a line through the knee center, perpendicular to Tr in the transverse plane (Fig. 1B).

The long axis of the tibia (L) is the line running through the knee center (O) and the center of the ankle (C) (Fig. 4).

The tibial length (OC) is the length of the line joining O and C (Fig. 4).

The tibial plateau widths are the medial plateau width (W7), lateral plateau width (W9), and overall width (EF), and are measured along the transverse axis (Tr). The medial margin (E) and lateral margin (F) were located in the transverse plane by intersection with Tr (Figs. 1B and 2A).

The tibial plateau depths are overall depths, plus anterior and posterior projections, and were recorded for medial and lateral plateaus (Ma, Mp, La, Lp). Overall depths were the distances between A and G (medial) and B and H (lateral) along the anteroposterior axis (AP)—see Fig. 2A.

The interspinous width (W8) and intercondylar depth (DI) are both indicated in Fig. 2A.

The transmalleolar width (MmMl) is the length of a line joining the tips of the malleoli, estimated from the medial and lateral perspectives (Fig. 4A). In the transverse plane, this line is referenced to the center of the knee (Fig. 1B) and the center of the ankle (Fig. 2B).

The tibial plateau margin varus angle (θ) is the angle in the frontal plane between the transverse axis (Tr) and a line joining the medial (E) and lateral (F) margins of the tibial plateau (Fig. 4A).

The tibial plateau surface varus angle (θ′) is the angle in the frontal plane between Tr and a line joining the bottom of the concavity on the medial side (J) and the peak of the convexity on the lateral side (K) (Fig. 4A).

The tibial plateau posteroinferior tilt angles are the medial plateau (λm)—the angle in the sagittal plane between the anteroposterior axis (AP) of the tibia and a line joining the anterior margin (A) and posterior margin (G)—and the lateral plateau (λl)—with a similar construction using the anterior (B) and posterior (H) margins (Fig. 4B).

The tuberosity lateral deviation (ν) is the peak of the tuberosity (N) located in the transverse plane at the midpoint of the insertional width of the ligamentous patellae. Lateral angulation (ν) of N from the anteroposterior axis (AP) in the transverse plane was measured with reference to the knee center (Fig. 1B).

The tibial torsion (μ) is defined as the angle between the line representing transmalleolar width (MmMl) and the transverse axis (Tr) of the tibial plateau in the transverse plane (Fig. 1B).

The foot rotation (α) is the angle between the path of the second toe ray and the anteroposterior axis of the tibial plateau as viewed in the transverse plane (Fig. 1B). The angle was measured from photographs taken prior to disarticulation of the ankle (Fig. 1A). A negative angle denotes internal rotation.

The transmalleolar line, valgus tilt (ψ) is the angle between the transmalleolar line (MmMl) and the transverse axis (Tr) of the tibial plateau viewed in the frontal plane (Fig. 4A).

Statistical Analysis

Both paired and unpaired limbs were used to calculate means and standard deviations for each of the parameters.
the linear and angular parameters. To do this, measurements for each pair of limbs were averaged (n = 13), then combined with the measurements for the unpaired limbs (n = 5) to calculate means and standard deviations for the entire group (n = 18). The procedure was then repeated independently for male (n = 8) and female (n = 10) limbs. Differences between the genders were determined by unpaired two-tailed t tests.

Bilateral asymmetry of the parameters was assessed in two ways by combining the data for both genders, but only in relation to the 26 limbs that were paired. First, a left side versus right side comparison was made for each parameter using paired two-tail t tests. Second, a “small” side versus “large” side comparison was made using paired one-tail t tests. To do this, it was necessary to examine the data for each pair of limbs, and then determine which limb was “large” in relation to each parameter measured. For example, in one pair, the left limb might be designated “large” regarding tibial length, but “small” on the basis of tibial plateau width.

**RESULTS**

Data for the linear and angular parameters and the results of statistical analysis are reported in Table 1. For most linear parameters (10 out of 13), there were significant gender differences favoring males with the larger dimensions in each case (p < 0.005). However, tibial length was not one of these (p > 0.05). In contrast, gender differences occurred in only two angular parameters—tibial torsion and foot rotation. The significance was greatest for the latter (p < 0.005), and indicated a mean internal rotation for males and external rotation for females.

Correlations were sought between the various linear and angular parameters, by applying regression analysis. Several linear parameters showed high correlation when the combined data were analyzed. Tibial plateau width (EF) versus medial and lateral plateau depths (Ma + Mp, and La + Lp) gave = 0.9 in both cases. Plateau width and tibial length were also closely correlated, especially when the genders were treated separately (Fig. 5). The data indicate that for a given tibial length, the plateau width

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbols</th>
<th>All limbs (18)</th>
<th>Male (8)</th>
<th>Female (10)</th>
<th>p value</th>
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<tr>
<td><strong>Linear</strong></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Tibial length</td>
<td></td>
<td>353 (23.7)</td>
<td>357 (20.4)</td>
<td>349 (25.4)</td>
<td>NS*</td>
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<td>Tibial plateau widths</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medial plateau</td>
<td>W7</td>
<td>32 (3.8)</td>
<td>34 (3.9)</td>
<td>30 (2.2)</td>
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<tr>
<td>Lateral plateau</td>
<td>W9</td>
<td>33 (2.6)</td>
<td>35 (1.9)</td>
<td>31 (1.7)</td>
<td>&lt;0.005</td>
</tr>
<tr>
<td>Overall width</td>
<td>EF</td>
<td>76 (6.2)</td>
<td>81 (4.5)</td>
<td>73 (4.5)</td>
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<td>Tibial plateau depths</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>AP depth, medial</td>
<td>Ma + Mp</td>
<td>48 (5.0)</td>
<td>52 (3.4)</td>
<td>45 (4.1)</td>
<td>&lt;0.005</td>
</tr>
<tr>
<td>A projection, medial</td>
<td>Ma</td>
<td>24 (2.7)</td>
<td>26 (2.0)</td>
<td>22 (2.2)</td>
<td>&lt;0.005</td>
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<tr>
<td>P projection, medial</td>
<td>Mp</td>
<td>24 (2.9)</td>
<td>26 (2.0)</td>
<td>23 (2.7)</td>
<td>&lt;0.005</td>
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<tr>
<td>AP depth, lateral</td>
<td>La + Lp</td>
<td>42 (3.7)</td>
<td>45 (3.1)</td>
<td>40 (2.3)</td>
<td>&lt;0.005</td>
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<tr>
<td>A projection, lateral</td>
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<td>24 (2.7)</td>
<td>26 (2.0)</td>
<td>22 (2.2)</td>
<td>&lt;0.005</td>
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<td>Lp</td>
<td>18 (2.3)</td>
<td>19 (2.1)</td>
<td>17 (2.3)</td>
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<td>Interspinous width</td>
<td>W8</td>
<td>12 (1.7)</td>
<td>12 (0.9)</td>
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<td>Intercondylar depth</td>
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<td>52 (5.7)</td>
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<td>&lt;0.005</td>
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<td>Transmalleolar width</td>
<td>MmMl</td>
<td>61 (8.0)</td>
<td>66 (4.8)</td>
<td>56 (6.9)</td>
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<td><strong>Angular</strong></td>
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<tr>
<td>Margin varus angle</td>
<td>θ</td>
<td>2 (1.6)</td>
<td>2 (1.5)</td>
<td>1 (1.5)</td>
<td>NS</td>
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<td>Surface varus angle</td>
<td>θ'</td>
<td>5 (2.3)</td>
<td>6 (2.1)</td>
<td>5 (2.3)</td>
<td>NS</td>
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<td>PI tilt, lateral</td>
<td>λl</td>
<td>8 (3.8)</td>
<td>8 (3.7)</td>
<td>7 (3.9)</td>
<td>NS</td>
</tr>
<tr>
<td>PI tilt, medial</td>
<td>λm</td>
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<td>7 (2.2)</td>
<td>7 (3.0)</td>
<td>NS</td>
</tr>
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<td>Tuberosity, lateral deviation</td>
<td>ν</td>
<td>9 (3.8)</td>
<td>8 (3.2)</td>
<td>10 (4.0)</td>
<td>NS</td>
</tr>
<tr>
<td>Tibial torsion, lateral</td>
<td>µ</td>
<td>24 (9.3)</td>
<td>21 (4.9)</td>
<td>27 (11.0)</td>
<td>&lt;0.025</td>
</tr>
<tr>
<td>Foot rotation,*</td>
<td>σ</td>
<td>2 (10.6)</td>
<td>-3 (8.2)</td>
<td>11 (3.3)</td>
<td>&lt;0.005</td>
</tr>
<tr>
<td>Transmalleolar line, valgus tilt</td>
<td>ρ</td>
<td>15 (3.5)</td>
<td>16 (1.8)</td>
<td>14 (4.0)</td>
<td>NS</td>
</tr>
</tbody>
</table>

AP, anteroposterior; A, anterior; P, posterior; PI, posteroinferior.  
* Mean values in mm or degrees to the nearest whole number, with the standard deviation in parentheses.  
* Not significant (p > 0.05) on the unpaired two-tailed t test.  
* Negative angle denotes internal rotation. Only 10 limbs (6 male) were examined.
width was significantly greater in males. There was no correlation between any of the angular parameters, including the tibial plateau margin varus angle (θ) and the surface varus angle (θ').

Statistical analysis for bilateral asymmetry of the parameters showed no significant differences on the basis of right versus left side comparisons (p > 0.05). However, when "large" versus "small" side comparisons were made, significant asymmetry was noted for the tibial plateau margin varus angle (θ) (p < 0.005) and for the lateral deviation of the tuberosity (ν) (p < 0.025).

**DISCUSSION**

The relationships between the articular planes of joints and the functional axes of the bones are relevant to the kinematics of limbs, and therefore to the design and sizing of resurfacing components. Also, predisposition to some types of osteoarthritis may reside in abnormal limb geometry that causes uneven loading of the bearing surfaces (2). There is, therefore, a rationale for the systematic study of alignment and geometry with intent to define normal ranges for their values and normal relationships between them.

A major disadvantage to the study of geometry using limb segments is the lack of an extra-articular reference point. It is therefore necessary to devise a system for standardizing their orientation with reference to selected bone landmarks. One approach has been to study rotational variation at each end of the tibia relative to the center of the bone (10). However, to measure angles at the articulating surfaces (especially in the frontal plane), precise definition and location of the anterior surface of the tibia is essential. Because there are few distinctive landmarks at the midtibia, we have used the tibial plateau for this purpose. In particular, we have chosen to orientate our limb segments with reference to a defined transverse axis (Tr) that is effectively the maximal proximal tibial width apparent on computed tomography (CT) scans (10). Hence, this alignment represents near neutral rotation at the knee. We have also orientated our limbs relative to the longitudinal axis (OC). Our definitions of knee center (O) and ankle center (C) for proximal and distal origins of this axis are in general agreement with others (6,8). Also, this location of the knee center is very close to the midpoint of the tibial plateau as measured in radiographs taken in both frontal and sagittal planes (3).

Our data on linear parameters are in general agreement with Farrally and Moore (6), who reported the mean tibial length for Caucasians to be 373.42 mm (S.D. = 24.56 mm) as measured from the most proximal point on the intercondylar eminences to the most distal point on the malleolus. However, they also examined linear proportions in...
negroids, in which they confirmed a generally longer and slimmer bone as compared to Caucasians. The correlations we found between various tibial linear dimensions, their symmetrical distribution in the limb pairs, and the size differences between genders all reflect previous findings for the femur (12,13,16).

Angular parameters were clearly different from linear ones in the greater variability and lack of correlation between them (Table 1). This again reflects our findings for the femur (16). Thus, if aberrant limb geometry can predispose to osteoarthritis, this study would clearly implicate the angular parameters. In support of this, abnormal alignment of joint surfaces has been associated with the majority of arthritic knees (3), although one cannot distinguish cause from effect in these cases. Another feature was the bilateral asymmetry noted for two parameters. The first was the relative coronal tilt of the bearing surface (θ) with reference to the long axis of the tibia. This is interesting for its implication regarding onset of unilateral arthritis through abnormal load bearing on one side only. The other parameter featuring asymmetrical distribution was the lateral deviation of the tuberosity (v), which is clinically relevant to patellofemoral alignment. A normal value of 14° has been reported (9), although in relation to the transverse axis of the tibial plateau defined in this study, we found a mean value of 9°. Significant differences between genders were noted only for tibial torsion [defined by the malleoli (11,14,16)] and foot rotation. The greater lateral tibial torsion combined with external foot rotation in females represents a remarkable "kneeing-in" when the foot is positioned straight ahead in stance. However, we remain cautious about the validity of the observation in view of the extreme variability of foot rotation within our relatively small sample size.

There is work in progress to obtain a more complete survey of lower limb geometry, by combined analysis of data for femurs and tibiae from the same donors. As for a causal link between osteoarthritis (onset and/or pattern or progression) and aberrant geometry, the answer must likely await prospective radiographic surveys of sample populations. Ideally, one would assess limb geometry in normal young adults and subjects with asymptomatic osteoarthritis, and then relate subsequent radiographic changes of osteoarthritis to the initial parameters of alignment.

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REFERENCES

