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Tibial Slope is Highly Variable in Patients Undergoing Primary Total Knee Arthroplasty: Analysis of 13,546 Computed Tomography Scans

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ABSTRACT

The purpose of this study was to retrospectively measure with computed tomography (CT) the posterior tibial slope (PTS) to establish the average anatomy and the incidence of outliers in patients undergoing total knee arthroplasty (TKA). Our cohort included 13,546 arthritic patients: 8241 (61%) female; 5305 (39%) male. The average PTS angle was 7.2° ± 3.7° (range, −5° to 25°). The average of PTS angle of the males was 7.17° ± 3.82° and females was 7.24° ± 3.57°. A significant number of patients 35.0% (4149) were identified outliers in PTS. 1568 (11.6%) patients' PTS angle was less than 4°, 2581 (19.1%) patients' PTS angle was more than 10°. These data can be useful to determine optimum techniques and methodology to perform more accurate TKA.

Anatomical studies report high variability of posterior tibial slope (PTS) in the general population, varying from 7° to 14.7° [1,2]. Many methods of measuring PTS have been reported in the literature. Most studies based the measurement on conventional radiographs; however, these measurement methods had high variability. The heterogeneous techniques to measure the PTS with different anatomical references did not correlate to the results reported. The reference chosen influenced the PTS with variability up to 5° [3].

In previous studies, PTS was measured on lateral tibial radiographs. The quality of radiographs and the projection of the tibial plateaus influenced the accuracy of these measurements [1,2]. Magnetic resonance imaging (MRI) was used to measure PTS and showed medial and lateral tibial plateaus without being superimposed; however, the measurement of the tibial anatomic axes was unreliable with this technique [4,5]. Recently, computed tomography (CT) has been used to measure tibial slope and has been very useful for identifying bony landmarks and determining 3-dimensional (3D) geometry [6,7].

The long-term success of total knee arthroplasty (TKA) depends, in part, on the proper mechanic alignment of the prosthetic implants [8,9]. Posterior tibial slope plays an important role in sagittal knee alignment, postoperative range of motion (ROM) of the knee, anteroposterior stability of the knee, and compressive force of tibiofemoral joint [5,10,11]. Hofmann et al [1] suggested that when proximal tibia was resected at 8° or more than the anatomic angle of PTS, the incidence of the tibial subsidence increased. An improper PTS angle can also cause polyethylene wear, component loosening, and posterior cruciate ligament strain [1,12,13].

When performing TKA, surgeons have different strategies regarding the tibial slope. With conventional alignment systems, the proximal tibial resection is typically set at a 3°, 5°, or 7° PTS angle. In TKA surgical technique, both intramedullary and extramedullary alignment guides are commonly used. Chiu et al [2] reported that the difference between the use of extramedullary and intramedullary alignment to determine the posterior slope was found to be higher than 3°. There was no consensus about the proper slope angle for TKA.

In addition, surgeons do not assess the native tibial slope preoperatively, considering the average value in the nonarthritic population. The purpose of this study was to determine the PTS in more than 13,000 CT scans of arthritic patients undergoing TKA in an effort to

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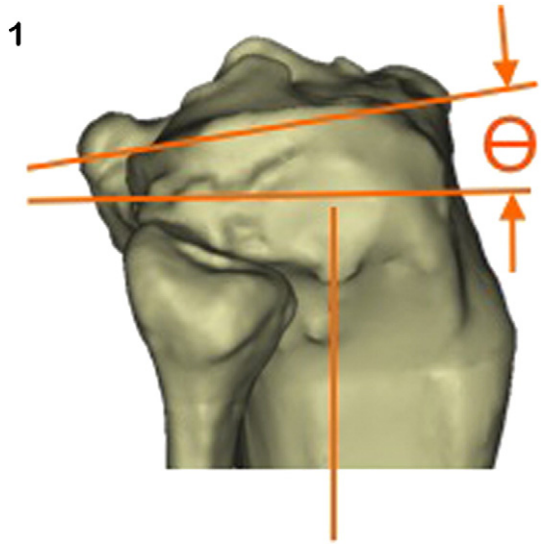

Fig. 1. Definition of the posterior tibial slope angle with the 3D reconstructions of the computed tomography scan.

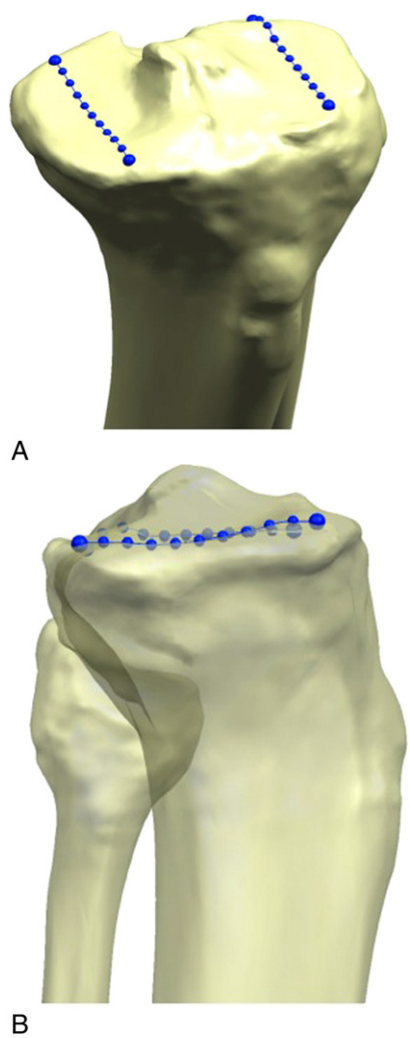

Fig. 2. (A) Twenty-two points were placed on the bony surfaces of the tibial plateau (blue points). Points were evenly distributed between the medial and lateral plateau. (B) A plane (red line) was best fit to all 22 points using a least squared error method.

Fig. 3. The talus center was found by locating the first CT slice that completely bisects the talus.

determine both average anatomy and the incidence of "outliers" in this population.

Material and Methods

CT scans of 13,546 arthritic patients undergoing TKA were analyzed using Amira® visualization software (Visual Science Group, Burlington, MA, USA) and NX computer-aided design software (Siemens Corporation, Berlin, Germany). All CT scans included the hip, knee, and ankle. Three-dimensional reconstructions were performed on each scan and key landmarks were identified in Amira software. The PTS angle is

Fig. 4. The center of the proximal tibia was calculated by sectioning the tibial 10 mm below the joint line and then determining the geometric center of that cross section.

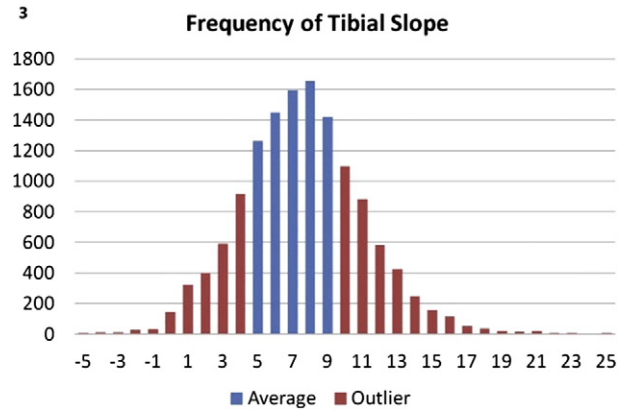

Fig. 5. The frequency of each value of posterior tibial slope angle is shown in the graphic.

defined between the posterior inclination of the tibial plateaus and the mechanical axis of the tibia in the sagittal plane (Fig. 1). The inclination of the tibial plateaus is defined by best fitting a plane on top of the bony surfaces of the medial and lateral tibial plateaus (Fig. 2A). To define the best fit plane on the tibial plateaus, we used an automated software that utilized a least squared error algorithm and 22 points that were evenly distributed on the medial and lateral tibial plateaus. Points were matched between the medial and lateral plateau at the lateral view of the tibial plateau (Fig. 2B).

The mechanical axis was defined as the line connecting the center of the proximal tibia and the center of the talus. The talus center was found by locating the first CT slice that completely bisected the talus (Fig. 3). Then the medial, lateral, anterior, and posterior margins were identified that allowed the computer to find a precise center point. The center of the proximal tibia was calculated by sectioning the tibial 10 mm below the joint line and then determining the geometric center of that cross section (Fig. 4).

All engineers involved with this study were trained in the use of Amira software, NX software, and knee anatomy. Engineers were selected from DePuy, Synthes Joint Reconstruction Company, Warsaw, IN USA. CT scans, which we measured for our study, were used for the patient-specific knee prosthesis. To assess reliability of the tibial mechanical axis measurement, a subsample of 11 engineers was identified to perform a repeat reading of CT scans. Engineers were blinded to the test. Six replicates were completed for 10 CT scans, for a total of 60 measures. All repeat measurements of tibial mechanical axis were $\pm 0.1°$, showing high reliability.

The patient's anatomy was defined as an outlier if the PTS deviated more than 3° from the average. Eighty-seven percent of the CT scans were performed in North America (n = 11,739). The remainder were performed in Europe (n = 1228), Asia (n = 319), Australia (n = 186), Middle East (n = 43), and Africa (n = 31). Sixty-one percent were female (n = 8241) and 39% were male (n = 5305). Patients' heights were measured and the relationship between height and PTS was analyzed. Limb alignment was considered varus in 81% (n = 11,021) valgus in 19% (n = 2525) with a range from 27° varus to 22° valgus. Average patient age was 65.4 ± 10.3. All data were collected and analyzed utilizing Microsoft Excel software (Microsoft® Corporation, Redmond, WA). Data were analyzed using ANOVA analysis.

Results

The average PTS angle was 7.2° ± 3.7° (range, −5° to 25°) (Fig. 5). The average of PTS angle of the males was 7.17° ± 3.82°; females, 7.24° ± 3.57°. Outliers in PTS were identified in 35.0% of scans (Fig. 6). The outlier patient data are shown in Table 1. No significant differences were found between male and female data.

PTS was highly variable in all geographic regions. The least variable region was Australia and most variable was Africa. The North American region was in the midrange (Table 2).

The average of PTS of the patients who were short (<5'1"; n = 921) had significantly higher PTS when compared with tall patients (>6'0"; n = 1028).

Patients with significant varus deformity (>10°; n = 745) had significantly higher tibial slope than the patients who had significant valgus deformity (>−10°; n = 207).

Patients with significant femoral bow (>5°) had significant higher tibial slope than the patients without femoral bow (Table 2).

Discussion

The PTS angle is highly variable in the population of patients undergoing TKA. Our report is the largest study to evaluate patients' PTS using modern CT scan data with 3D computer modeling. Thirty-five percent of arthritic patients were considered outliers.

In the literature, several anatomic studies reported variable PTS angles. Hofmann et al [1] reported preoperatively PTS mean of 7° (range, 2°–12°) in 33 arthritic patients with a standard weight-bearing lateral view. Dejour and Bonnin [14] described a PTS mean of 10° ± 3° in 281 nonarthritic knees. Bellemans et al [15] reported a range of PTS angles from 4° to 9° in 21 cadavers. Other studies have shown that

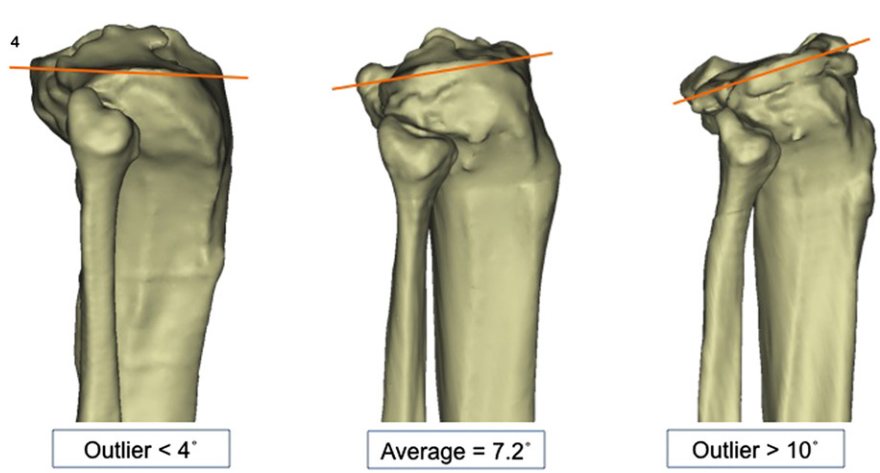

Fig. 6. Three-dimensional reconstructions of tibias and definition of the posterior tibial slope angles are shown. Left tibia is an outlier with posterior tibial slope angle of less than 4°. Middle tibia is a typical tibia with a posterior tibial slope angle of 7.2°. Right tibia is an outlier with a posterior tibial slope angle greater than 10°.

Table 1
Number of Patients Outside the Average ±3° for Posterior Tibial Slope.

Posterior Tibial Slope Angle	Female n[a] (%)	Male n[a] (%)	Total n[a] (%)
<4°	878 (10.7%)	690 (13.0%)	1568 (11.6%)
>10°	1550 (18.8%)	1031 (19.4%)	2581 (19.1%)

[a] n number of patients.

degeneration of the knee influences the PTS angle measurement. Matsuda et al [16] reported 30 osteoarthritic and 30 normal knees PTS angles and found the PTS medial tibia mean of 10.7° in the normal knees and 9.9° in the osteoarthritic knees, although not statistically significant. Bae et al [17] reported a PTS mean of 11.4° ± 4.5° in 386 arthritic knees. The variability of the PTS angles may relate to the arthritic condition of the knee. Our study identifies variability of the PTS angles in arthritic patients, which may help surgeons during TKA procedures.

Prior studies showed variable results of PTS angles. One of the reasons for these variable results was related to different methods of measurement employed on lateral radiographs, MRI, and CT. Measuring PTS with conventional radiographs has shown poor reproducibility [18]. Studies that used MRI for measuring the tibial slope attempted to improve reproducibility [4,5,19]. However, MRI images did not include the full length of the tibia, which compromised the measurement of the anatomic axis of the tibia. Hudek et al [19] measured PTS on MRI images and reported that the mean medial posterior slope was 3.4° smaller on MRI compared with those on radiographs. CT is a widely accepted imaging modality for identifying bony landmarks and determining 3D geometry [20]. The large sample size of CT scans in this study and the accuracy of the 3D measurements allow precise measuring of anatomic variables in a TKA patient population.

The measurement of the medial tibial slope also was shown to be different than the lateral tibial slope. Chiu et al [2] reported that the medial plateau posteriorly sloped 3° more than the lateral plateau. Matsuda et al [16] found the PTS mean in the medial tibial plateau of 10.7° (range, 5°–15.5°) and the mean PTS in the lateral tibial plateau of 6° (range, 1°–13°). Nunley et al [6] used 3D CT scans to measure the PTS angles and reported that an average medial PTS was 6.8° ± 3.3° on 2031 knees and the average of lateral PTS angle was 8.0° ± 3.3° on 364 knees of the patients' CT scans. In our study, we assessed PTS angles in 13,546 knees but did not measure the lateral and medial tibial slopes angles separately.

Many anatomical landmarks were identified to measure the PTS angles. Yoo et al [21] compared 5 different anatomical axes, which were mechanical axis, anatomic axis, posterior tibial cortical line, fibula shaft axis, and anterior tibial cortical line to measure the PTS angles. They showed that the mean PTS was different in all axes and all differences were statistically significant [21]. Brazier et al [22] reported 6 different methods of PTS measurements in 50 healthy patients. The differences in PTS angles ranged from 2.2° to 3.5°. Chiu et al [2] reported that PTS of medial tibial plateau was 11.5° ± 3.7° with the intramedullary alignment line and was 14.7° ± 3.6° with the extramedullary alignment. In our study, the mechanical axis of the tibia was determined as the line connecting the center of the proximal tibia and the center of the talus and was used to identify the proximal tibia top of the bony surfaces of the medial and lateral tibial plateaus.

Table 2
Natural Tibial Slope for Various Patient Groups.

Patients Sub Group	N	Avg	SD	*P*-Value[a]	95% Confidence Interval for Difference
Africa	31	5.77	6.06	<0.01	(−2.778, −0.244)
Asia	319	9.49	4.52		(1.799, 2.603)
Australia	186	6.14	3.14		(−1.663, −0.626)
Europe	1228	6.15	3.78		(−1.343, −0.925)
Middle East	43	7.85	4.53		(−0.364, 1.786)
North America	11,739	7.29	3.59		N/A (control)
Female	8241	7.24	3.57	0.228	(−0.049, 0.205)
Male	5305	7.17	3.82		
Tall (>6'0")	1028	6.98	3.89	0.01	(−0.835, −0.112)
Short (<5'1")	921	7.46	4.23		
Significant varus	745	8.69	5.29	<0.01	(1.525, 2.188)
Significant valgus	207	7.00	4.12		(−0.325, 0.654)
Femoral bow +5	345	7.23	4.18	<0.01	(−0.484, 0.360)
No femoral bow	1810	7.17	3.56		

[a] Anova analysis.

Restoration of the limb axial and sagittal alignment is crucial in TKA. PTS is recognized as an important factor to achieve sagittal alignment [10]. Several studies have reported that the tibial slope has a direct effect on translation of the tibiofemoral joint, the location of center of rotation, the screw home mechanism, and the knee ligament strain [5,23]. The PTS affects the stabilizing effect of the anterior cruciate ligament [24]. Every 10° increase in PTS was associated with a 6 mm increase in anterior tibial translation in the monopodal stance [14]. Increased PTS is associated with reduced varus-valgus, anterior-posterior, and rotational tightness in flexion [25]. However the effect of the increased PTS for knee ROM [13] is controversial. It has been reported that increased PTS correlated with increased ROM [15]. Lombardi et al [26] reported that ROM was better in the patients with less than 3° of PTS than it was in the patients with more than 3° of slope. However, Kansara and Markel [27] compared ROM between 0° and 5° PTS angle groups and observed that larger PTS angles did not increase postoperative ROM.

The proximal tibial cut performed in TKA surgery uses conventional instrumentation and bases the implant's position on the average anatomy, typically cutting the tibial at 3°, 5°, or 7° of slope. Preparing the proximal tibia with conventional tibial guides and average anatomy can cause malposition of the tibial plate in the outlier patients. In the extramedullary technique, the reference was defined using the anterior cortex of the tibia. Han et al [3] reported that the angle between mechanical axis of tibia with anterior tibial cortex was 2.2° ± 0.92°. Bae et al [17] found that the differences in PTS angles based on anatomical axis and anterior cortex of tibia ranged from 2.1° to 2.3°. Our study showed that 35% of patients were considered outliers and should be recognized preoperatively for proper adjustment of tibial guides. Hofmann et al [1] reported that when a tibia was resected at 8° or more, different than the normal anatomic angle of PTS, the incidence of tibial subsidence seemed to increase. Bai et al [28] found that decreasing tibial slope decreased flexion gap in TKA. However, extreme PTS angles caused anteroposterior instability, which may induce anterior subluxation of the tibia and may cause aseptic loosening [28]. Also inadequate PTS causes tight flexion gap, which may entail limitation of femoral rollback and limited ROM [1,25].

Our study has several limitations. The present study was not designed to determine if this anatomical difference led to poor outcomes for implant arthroplasty in TKA. No postoperative alignment data or outcome data were considered. Another limitation of this study, it was performed in osteoarthritic knees and our findings should not be extrapolated to normal tibial anatomy. This study was designed to determine variations of the PTS in arthritic knees. Finally, medial and lateral PTS measurements were not performed in our study, which would give more insight to understand the anatomy of the proximal tibia.

Conclusions

Our data showed that PTS slope is highly variable in arthritic patients. Anatomical studies were highly variable as shown in the literature. In our study, we determine more reliable PTS angles with the large cohort. These data may indicate that surgeons should be aware of the variability of the tibial slope in patients undergoing TKA.

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