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Original article

Three-dimensional lower extremity alignment in the weight-bearing standing position in healthy elderly subjects

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Abstract
Background. Although assessment of lower extremity alignment is important for the treatment and evaluation of diseases that present with malalignment of the lower extremity, it has generally been performed using only plain radiographs seen in two dimensions (2D). In addition, there is no consensus regarding the criteria for quantitative three-dimensional (3D) evaluation of the relative angle between the femur and tibia. The purpose of this study was to establish assessment methods and criteria for quantitatively evaluating lower extremity alignment in 3D and to obtain reference data from normal elderly subjects.
Methods. The normal alignment of 82 limbs of 45 healthy elderly subjects (24 women, 21 men; mean age 65 years, range 60–81 years) was analyzed in 3D with regard to flexion, adduction–abduction, and rotational angle of the knee in the weight-bearing, standing position. The obtained computed tomography (CT) and biplanar computed radiography (CR) data were used to define several anatomical axes of the femur and tibia as references.
Results. In the sagittal plane, the mean extension–flexion angle was significantly more recurvatum in women than in men. In the coronal plane, the mean 3D hip-knee-ankle angle was more varus by several degrees in this Japanese series than that in a Caucasian series reported previously. Regarding rotational alignment, the mean angle between the anteroposterior axis of the tibia and the transepicondylar axis of the femur in this series was slightly larger (externally rotated) than that of previously reported Japanese series examined in the supine position.
Conclusions. These data are believed to represent important references for 3D evaluation of morbid lower extremity alignment in the weight-bearing, standing position and are important for biomechanical research (e.g., 3D analyses of knee kinematics) because the relative angles between the femur and tibia are assessed three-dimensionally.

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Introduction

Lower extremity alignment is determined by both the spatial relation between the femur and tibia and by the geometry of these bones. Assessment of lower extremity alignment is important when determining and evaluating treatment for diseases that present with abnormal alignment in the lower extremities, such as knee and hip arthritis, patellar dislocation, and congenital malalignment.[1–13] In the field of orthopedic surgery, lower extremity alignment is generally assessed two-dimensionally (2D) on plain radiographs using the hip-knee-ankle angle or the tibiofemoral angle in the coronal plane alone.[11,14,15] However, 2D radiographic measurements are affected by the position of the radiation source and the orientation of the subject's pelvis and lower extremities.[16] Therefore, the accuracy and reproducibility of this method are insufficient for detailed investigations. In addition, rotational alignment cannot be assessed on plain radiographs.

Despite remarkable recent developments in medical imaging technologies that enable visualization of the three-dimensional (3D) geometry of bone and alignment of the lower extremity, few studies have reported quantitative 3D evaluations of lower extremity alignment in the weight-bearing, standing position using 3D digital bone models. In addition, there remains a lack of consensus regarding the criteria for quantitative 3D assessment.

As previously reported, we developed a method for assessing 3D lower extremity alignment in the standing position using 3D digital bone models; this system has been in clinical use since 2002.[17,18] To evaluate morbid alignment in the lower extremities of patients with hip and knee arthritis and other diseases, it is vital to obtain normal data of lower extremity alignment from healthy subjects as a reference. One of the purposes of this study was to obtain these reference data by quantitative, 3D evaluation of lower extremity alignment in healthy elderly subjects so we could compare them with data from osteoarthritis patients' alignment, thereby increasing our knowledge of the clinical state of the disease in future research. Another purpose was to establish the criteria for these evaluations.

Materials and methods

This study was performed according to the protocol approved by the investigational review board of our hospital and Niigata University. All subjects gave informed consent to participate in this study.

Subjects

We assessed 82 limbs of 45 healthy elderly subjects (24 women, 21 men; 37 bilateral and 8 unilateral) who had no pain, history of trauma, knee injury, knee complaints, or radiographic abnormality in the lower limb; they also had no osteoarthritis or rheumatoid arthritis. Unilateral data had been previously collected for another study, and the subjects' opposite lower limbs did not have any of the above-mentioned disorders. The average age of the subjects was 65 years (range 60–81 years).

Three-dimensional digital bone models

Computed tomography (CT) scans with a 2-mm interval were obtained of the femur and tibia of each subject. A 3D digital model of each femur and tibia was reconstructed from the CT data using 3D visualization and modeling software (Zedview; LEXI, Tokyo, Japan) and displayed as a point group. The anatomical coordinate systems were established using 3D model digitizing software (Model Viewer; LEXI) according to the method of Sato et al.[17,18] (Fig. 1). Several anatomical reference points (described below) were digitized, and the reference axes used in the present study were then installed.

Three-dimensional image-matching procedure

Biplanar computed radiography (CR) images of the subjects' lower extremities were obtained in the weight-bearing, standing position with the knee fully extended and toes in the neutral position using the 3D lower-extremity alignment assessment system previously reported.[17–19] These images were downloaded to a personal computer. Using the camera calibration technique,[17] we projected the cited 3D digital bone models onto the biplanar CR images by matching the silhouettes of the digital models to the contours of the respective CR bone images via 3D rotation and translation.

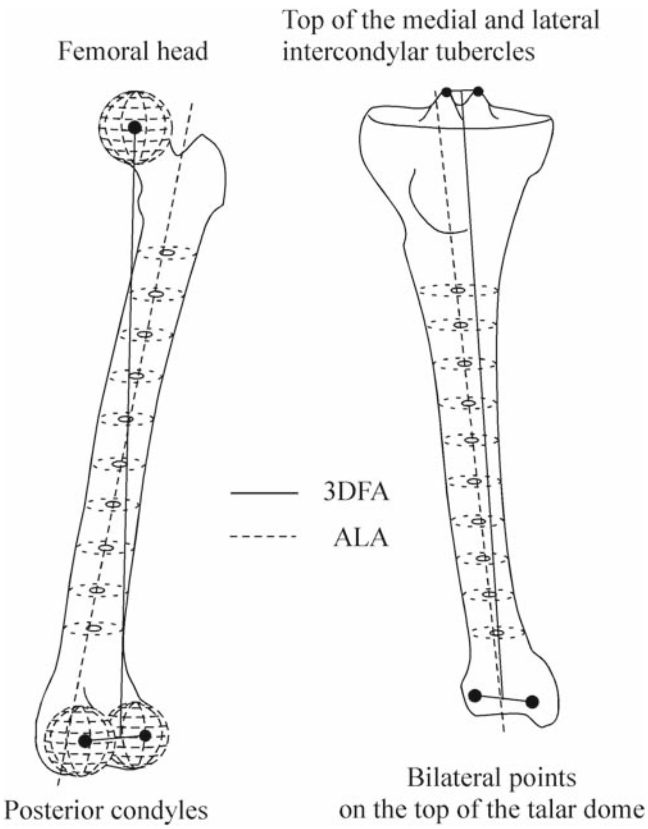

Fig. 1. Bony reference points and anatomical axes defined on the femur and tibia. *Continuous lines*, three-dimensional functional axes (*3DFA*) [11]; *dotted lines*, anatomical longitudinal axes (*ALA*)

After these image-matching procedures, a 3D view of the digital bone model that accurately reproduced the spatial relation between the femur and the tibia at the time of CR projection was displayed; and all alignment parameters (described below) were automatically calculated. The maximum spatial errors of this procedure were 0.5 mm when determining distance and 0.8° when determining orientation.[17] The maximum errors in the proposed image matching procedure for determining the relative pose and position between the femur and tibia were 1.6 mm distance and 1.5° orientation.[19] With regard to the reproducibility of the calculated angles, the maximum interobserver error, including all processes of the analysis, was 1.9°, and the maximum intraobserver error was 0.8°.

Definitions of anatomical parameters

Anatomical axes

For true 3D evaluation of lower extremity alignment, the anatomical reference axes themselves must also be defined in 3D. To define the anatomical longitudinal axes of the femur (ALA-f) and tibia (ALA-t) in 3D, a

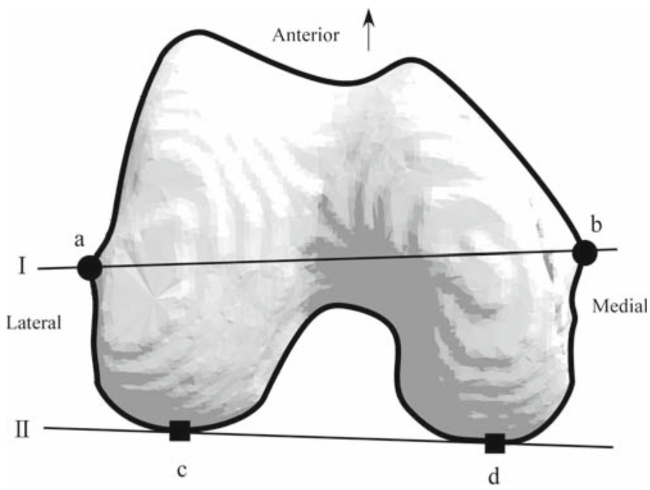

Fig. 2. View of the distal femur. *a*, *b*, prominences of the medial and lateral femoral epicondyles; *c*, *d*, posterior-most points of the medial and lateral femoral condyles; *I*, clinical transepicondylar axis (CTEA); *II*, femoral posterior condylar axis (PCA-f)

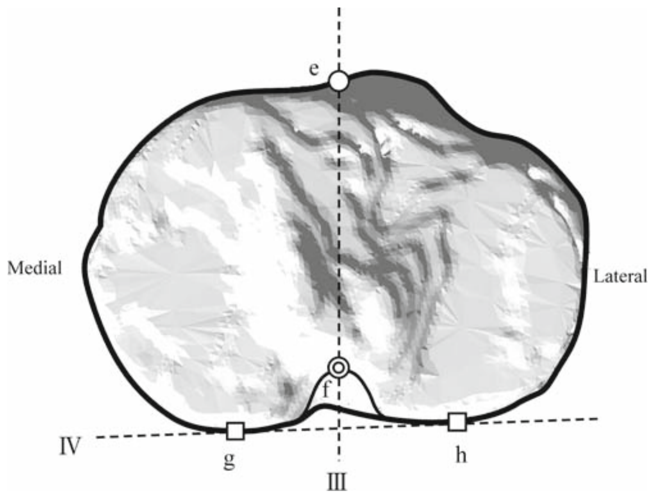

Fig. 3. View of the proximal tibia. *e*, medial edge of tibial tubercle; *f*, anterior-most point of insertion of the posterior cruciate ligament; *g*, *h*, posterior-most points of medial and lateral condyles. *III*, anteroposterior axis of the tibia (APA-t); *IV*, tibial posterior condylar axis (PCA-t)

point group centroid was calculated automatically for the 10 respective cross-sectional planes that divide the diaphysis into 11 equal sections. The ALA was defined as a regression line obtained from approximating distances from these 10 centroids by the least square method (Fig. 1). The 3D functional axes of the femur (3DFA-f) and tibia (3DFA-t) were defined according to the method proposed by Sato et al.[18] 3DFA-f was defined as a line connecting the center of the femoral head and the midpoint of the spheres that represent the medial and lateral posterior femoral condyles. 3DFA-t was defined as a line connecting the midpoint of the eminences of the medial and lateral tibial spines and the center of the ankle joint. Additional axes were defined to assess rotational alignment. For the femur, the posterior condylar axis (PCA-f) [20,21] was defined as a line connecting the posterior-most points of the medial and lateral femoral condyles; and the clinical transepicondylar axis (CTEA) [22,23] was defined as a line connecting the prominences of the medial and lateral epicondyles (Fig. 2). For the tibia, the posterior condylar axis (PCA-t) [24] was defined as a line connecting the posterior-most points of the medial and lateral tibial condyles. The anteroposterior axis of the tibia (APA-t)[25] was defined as a line connecting the anterior-most point of the tibial insertion of the posterior cruciate ligament (PCL) and the medial edge of the tibial tubercle[26] projected onto the axial plane of the tibial coordinate system (Fig. 3).

Extension–flexion angle

The anatomical extension–flexion angle of the knee was defined in two ways: (1) as the angle between ALA-f and ALA-t projected onto the sagittal plane of the femoral coordinate system, termed the 3D anatomical flexion angle (3DAFA); and (2) as the angle between 3DFA-f and 3DFA-t projected onto the same plane, termed the 3D mechanical flexion angle (3DMFA) (Fig. 4). We believe that these angles are each alternative for conventional parameters for evaluating limb alignment: 3DAFA is the 3D version of the definition of knee flexion angle, which is generally utilized for clinical examination; and 3DMFA is the 3D and sagittal version of the conventional hip-knee-ankle angle (HKA).

Adduction–abduction angle

The adduction–abduction angle was also defined in two ways: (1) as the angle between ALA-f and ALA-t projected onto the femoral coronal plane, termed the 3D tibiofemoral angle (3DTFA); and (2) as the angle between 3DFA-f and 3DFA-t projected onto the same plane, termed the 3D hip-knee-ankle angle (3DHKA) (Fig. 5). These two angles are literally 3D versions of TFA and HKA, respectively.

Rotational angle

The relative rotational angle between the femur and tibia at the knee joint was defined in two ways: (1) as the angle between PCA-f and PCA-t projected onto the axial plane of the femoral coordinate system, termed the posterior rotational angle (PRA); and (2) as the angle between CTEA and APA-t projected onto the same plane, termed the functional rotational angle (FRA). We defined PRA as a stable angle for accurate assessment, such as motion analysis. FRA was defined particularly for considering the target alignment of the implants of total knee arthroplasty (Fig. 6).

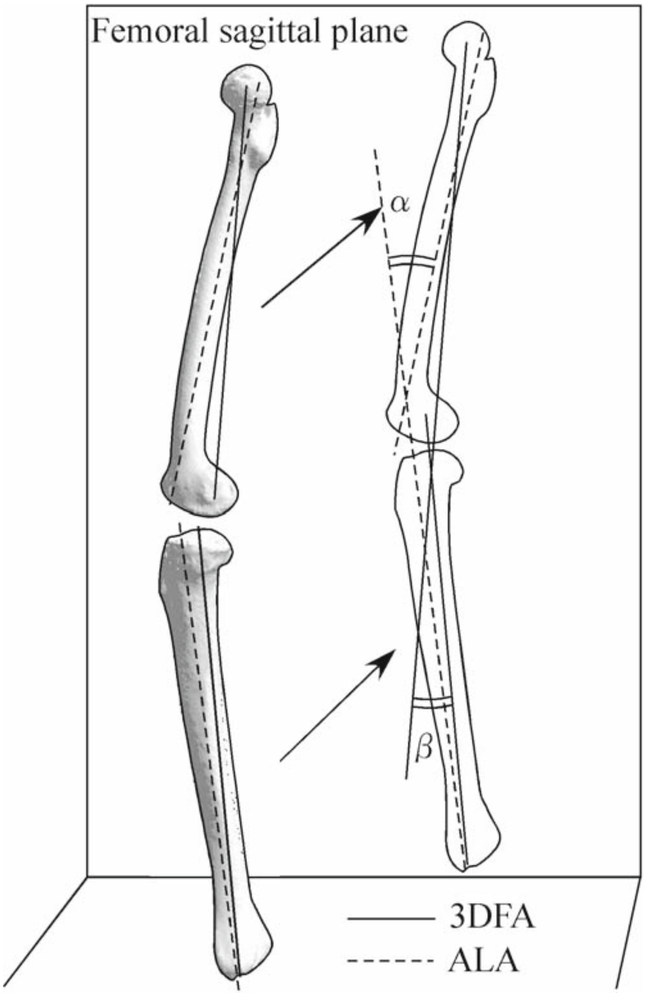

Fig. 4. Reference axes projected onto the femoral sagittal plane. α, 3D anatomical flexion angle (3DAFA), defined as the angle between the ALA-f and ALA-t; β, 3D mechanical flexion angle (3DMFA), defined as the angle between 3DFA-f and 3DFA-t

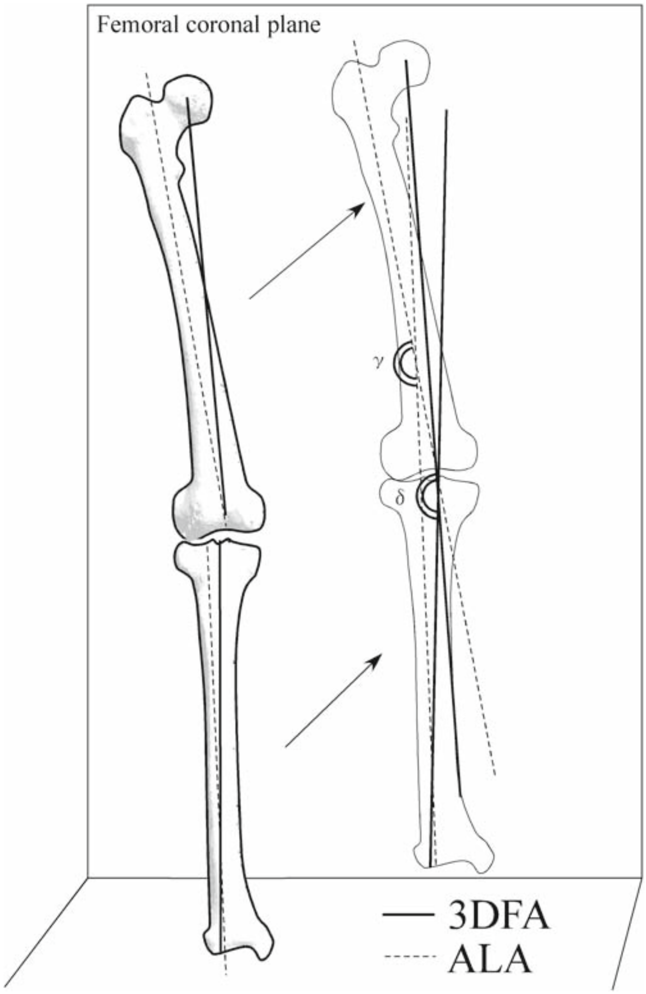

Fig. 5. Reference axes projected onto the femoral coronal plane. γ, 3D tibiofemoral angle (3DTFA), defined as the angle between the ALA-f and ALA-t; δ, 3D hip-knee-ankle angle (3DHKA), defined as the angle between the 3DFA-f and 3DFA-t

Statistical analyses

Differences in all of the angles for sex were assessed using Student's *t*-test, with the level of significance set at $P < 0.05$. The associations between each plane were investigated using regression analysis.

Results

The mean value and standard deviation of each parameter are described in Table 1. Both of the extension–flexion angles (3DMFA and 3DAFA) were significantly ($P = 0.03$) lower (genu recurvatum) in women than in men; in contrast, no difference was found for adduction–abduction or rotational angles with regard to sex. There were no significant correlations between any combinations of three planes with either of the total or by sex. Although all the angles demonstrated near-normal distributions, wide variations were shown for all angles.

Discussion

We conducted a 3D assessment of alignment of the lower extremities in healthy subjects in weight-bearing, standing position using an anatomical coordinate system established by various bony landmarks on 3D digital bone models. The use of 3D digital models reconstructed from CT data enabled accurate assessment of several clinically important bony landmarks, including the femoral epicondyles and insertion of the posterior cru-

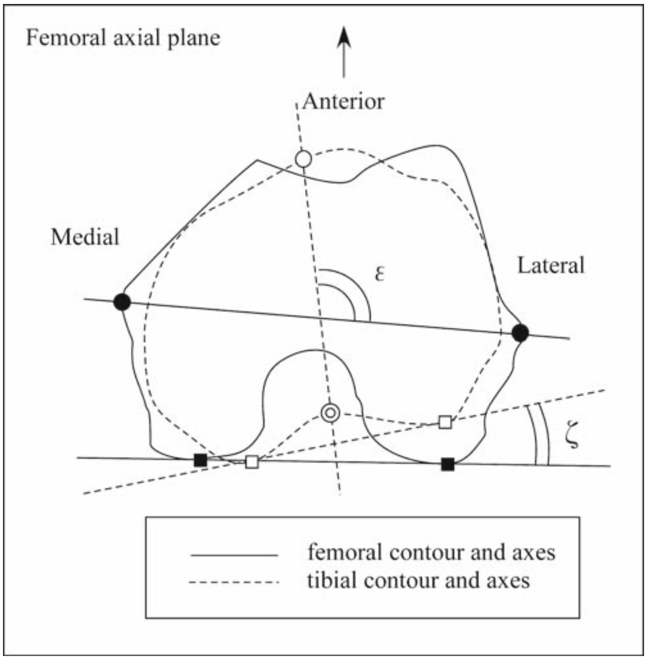

Fig. 6. Reference axes projected onto the femoral axial plane. ε, functional rotational angle (FRA), defined as the angle between the PCA-f and PCA-t; ζ, posterior rotational angle (PRA), defined as the angle between the CTEA and APA-t

ciate ligament (PCL), which are particularly useful for evaluating rotational alignment between the femur and tibia. Cooke et al.[14] also reported a 3D evaluation of lower extremity alignment in the standing position using a similarly calibrated frame but without utilizing the 3D geometry of bone; thus, the important landmarks described above could not be evaluated and accurate evaluation of rotational alignment could not be achieved. Taking into account that recent remarkable development in CT and magnetic resonance imaging (MRI) technology enables accurate 3D information of bone geometry to be obtained relatively easily, we think that it is reasonable to use this 3D information for precise evaluations of lower extremity alignment.

Regarding the definitions of the parameters for alignment evaluations, all angles that describe a relative angle between the femur and tibia were projected onto respective planes of the femoral coordinate system in the present study. Although it was a relatively complicated procedure, we believe that all angles should be projected onto the planes of any anatomical coordinate system of the subject's own bone, and that it was the only way to eliminate the measuring errors caused by the postures of the subjects and the positions of the radiation sources used for conventional 2D evaluation by plain radiography.[16]

Although we found no previous studies that reported evaluation of lower extremity alignment using the same 3D concept as that proposed in the present study, several authors have reported their findings of entire lower extremity alignment in each plane, as follows. With regard to sagittal alignment, Minoda et al. were the first to report a 2D evaluation[10] of healthy subjects in the standing weight-bearing position; they used lateral plain radiography, which revealed a knee flexion angle of 0.8° ± 4.2° (range –6.2° to 9.2°). Compared with the results of their study, the mean 3DMFA in the present study is slightly more recurvatum, probably reflecting differences in the definitions of the reference axes in the two studies: In the present study, all reference axes were defined three-dimensionally, whereas in Minoda's study they were defined two-dimensionally. Another factor possibly reflecting the difference in the results between the two studies was that they used the fibula as the lower limb axis, whereas we used the tibia (ALA-t). With regard to differences between the sexes, our results found significantly more extension (genu recurvatum) in women, as reported by Nguyen and Shultz.[27] We believe that the results of the present study regarding the knee extension–flexion angle (e.g., 3DAFA and 3DMFA) may be used as reference data when evaluating the knee flexion angle anatomically in such situations as knee motion analysis or accurate clinical assessment of range of motion.

Regarding coronal alignment, Moreland et al. reported that the mean knee adduction–abduction angle measured on plain long-leg anteroposterior radiography was 178.5° for the right and 178.9° for the left.[11] Cooke et al. also reported coronal alignment of the lower extremity as the HKA angle in healthy subjects in the standing position[14] and described almost the same alignment as that reported by Moreland et al. Compared with these studies, the mean adduction–abduction angle (3DHKA) in the present study was slightly greater (genu varum). The results of coronal alignment (3DHKA and 3DTFA) in the present study were almost the same as the results of two previous studies[13,28] that reported coronal alignment of lower extremities in Asian populations. Therefore, we believe that the difference in coronal alignment between the results of our series and that of Moreland et al.'s study reflected a racial difference, rather than a difference in the methodologies.

Akagi et al.[26] measured the rotation angle of the knee joint in healthy subjects in the supine position, reporting a value of 0° ± 2.8° (range –6.3° to 5.2°). Compared with this previous study, the results of the present study show slightly greater external rotation of the tibia against the femur, probably reflecting differences in the definitions of the reference axis of the femur and in the subjects' posture in the two studies. In the Akagi et al. study, the surgical transepicondylar axis[26] (SEA) — defined as the line connecting the sulcus of the medial epicondyle and

Table 1. Angles: means, standard deviations, and ranges

Parameter	Male	Female	Total
Age			
Mean	65.6	64.8	65.1
SD	5.0	5.0	5.0
Range	60–74	60–77	60–77
Extension–flexion angle (°)			
3DAFA			
Mean	6.1	4.0	5.0
SD	5.1	6.0	5.6
Range	–6.5 to 5.1	–6.8 to 6.0	–6.8 to 18.3
3DMFA			
Mean	–2.2	–5.1	–3.8
SD	5.3	6.0	5.9
Range	–15.7 to 5.3	–15.5 to 6	–15.7 to 9.7
Adduction–abduction angle (°)			
3DTFA			
Mean	177.5	176.6	177
SD	2.5	2.5	2.5
Range	172.1–182	171.7–182	171–182
3DHKA			
Mean	181.8	181.8	181.8
SD	2.2	2.6	2.4
Range	177.8–186.5	176.6–188.4	176.6–188.4
Rotation angle (°)			
PRA			
Mean	–1.4	–2.6	–2.1
SD	6.9	6.4	6.6
Range	–14.1 to 12.1	–14.8 to 14.3	–14.8 to 14.3
FRA			
Mean	87.3	84.4	85.7
SD	4.5	6.0	5.1
Range	70.5–104	62.5–99.1	64.9–106.0

AFA, anatomical flexion axis; MFA, mechanical flexion axis; TFA, tibiofemoral angle; HKA, hip-knee-ankle angle; PRA, posterior rotation angle; FRA, functional rotation angle

the lateral epicondyle—was utilized, whereas the CTEA was utilized in the present study because the sulcus of the medial epicondyle was sometimes not present.[29] With regard to the subject's posture, the present study is the first in which the relative rotational angle between the femur and tibia was assessed in the weight-bearing, standing position with the knee fully extended; this angle was assessed in the supine position in the previous studies. Therefore, we believe that the tibia was more externally rotated against the femur in this position than in the supine position, achieving "screw-home movement" during terminal extension of the knee.[30]

Throughout the results, the present study shows marked variability among individuals, and there was no clear correlation between each plane. These facts suggest the difficulty of anticipating entire limb alignment from one parameter in any plane. Assessment of each parameter is thought to be required for detail inspections.

There were several limitations in this study. First, the number of subjects was relatively small because it was difficulty finding a large number of volunteers of the required age who were healthy and who were willing to undergo a CT scan of the entire lower extremity. A larger number of subjects is considered necessary to provide more reliable reference data. Second, the radiation dose delivered during this procedure was higher than that for a plain radiograph because CT scanning was used. New methods for producing 3D digital bone models from images taken by other radiation-free devices, such as MRI, are currently under development. Finally, the definition of "healthy" subjects in this study was based on our subjective determinations. It is possible that subjects who did not have any pain or disease in the lower extremity during the period of this research may develop disease later. Elderly subjects were investigated in this study because we thought that the above possibility would be reduced if the ages of the subjects were relatively high.

In the present study, normal alignment of the lower extremities was analyzed in three dimensions in the weight-bearing, standing position using several anatomical axes defined three-dimensionally. We also suggested definitions of anatomical extension–flexion, adduction–abduction, and rotational angle of the knee, which were then measured three-dimensionally in healthy subjects. These data are believed to represent important references for determining the above angles in 3D knee motion analysis and in other accurate evaluations regarding 3D knee alignment.

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