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Evaluation of the 3-Dimensional, Weight-bearing Orientation of the Normal Adult Knee

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Abstract

The purpose of this study was to use 3-dimensional, weight-bearing images corrected for rotation to establish normative data of limb alignment and joint line orientation in asymptomatic, adult knees. One hundred adults (200 lower extremities) were recruited to receive weight-bearing, simultaneous biplanar imaging of both lower extremities. Multiple radiographic parameters were measured from 3D images, corrected for limb rotation. 70.0% of knees were in neutral, 19.5% in varus, and 10.5% in valgus overall alignment. Only 31 % of knees possessed both a neutral mechanical axis and the absence of joint line obliquity. There was substantial agreement between the 2D and 3D images for overall mechanical alignment ($\kappa=0.77$), but only a moderate agreement for joint line obliquity ($\kappa=0.58$). A substantial portion of asymptomatic adults possess either a varus or valgus mechanical alignment and joint line obliquity,

Introduction

Despite the long-term survivorship and clinical effectiveness of total knee arthroplasty (TKA), 15% to 30% of patients remain “unsatisfied” following a TKA (1–3). Traditionally, the success of TKA has been accepted to be dependent on achieving a lower extremity mechanical axis within 3° of neutral, and a tibial and femoral component position, or joint line, perpendicular to the mechanical axis in the coronal plane (4–8). However, recent data has challenged the importance of postoperative mechanical axis alignment in TKA. Parratte et al., in a review of 398 TKAs, demonstrated no improvement in the fifteen-year implant survival rate in patients within and outside of a postoperative mechanical axis of $0^\circ \pm 3^\circ$ (9).

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Recently, Bellemans et al. have introduced the concept of “constitutional varus,” which hypothesizes that correction to a neutral mechanical alignment may not be “normal” for a significant proportion of the population, as 32% of asymptomatic men and 17% of asymptomatic women possess a natural mechanical alignment of 3° of varus or more (10, 11). In conjunction with this principle, several surgeons have supported the restoration of the kinematic, rather than mechanical, alignment in TKA (12–14). The concept of an anatomic restoration of the joint line using a measured resection technique was initially introduced by Hungerford and Krackow, with the Porous-Coated Anatomical (PCA) Knee (15). This often required an anatomic, proximal tibial resection of 3° of varus. Similarly, the purpose of a kinematically aligned TKA is to align the angle and level of the distal joint line of the femoral component, posterior joint line of the femoral component, and joint line of the tibial component to those of the “normal” knee (13).

Therefore, the optimal target alignment in TKA remains controversial. However, despite the emphasis placed on clarifying the importance of alignment in TKA, there is a limited amount of data studying anatomic variables and alignment in normal, asymptomatic adults (11, 16, 17). Furthermore, while the importance of obtaining full-length, standing radiographs in assessing coronal alignment has previously been emphasized, (18, 19), two-dimensional (2D), plain radiography is also limited. Rotational attitudes due to the degree of deformity or anatomic variations such as femoral bowing, can affect standard measurements of limb alignment on 2D images (20, 21). While computed tomography (CT) scans allow 3D adjustments for limb rotation, they are obtained without weight-bearing, are time consuming, and impractical to routinely apply to clinical practice due to the high level of radiation exposure (22).

Recently, a new technology has been introduced, which utilizes novel technological advances in x-ray detection capability, allowing for data acquisition with approximately 1/10th of the radiation exposure of conventional radiographs (22). This system allows for the simultaneous acquisition of biplanar, standing, weight-bearing films, that can then be rendered into a 3D image corrected for rotation. The purposes of this study were to obtain 3D, weight-bearing, full-length lower extremity images corrected for rotation in asymptomatic adults, to establish 1) normative data of limb alignment and joint line orientation, 2) anatomic factors contributing to a varus or valgus alignment and the presence of joint line obliquity, 3) the degree of correlation for mechanical alignment and joint line obliquity between the lower extremities in the same subject, and 4) the capability of full length 2-dimensional (2D) images to predict the orientation measured on 3D images corrected for rotation. Our hypotheses are that 1) a large portion of patients will have either a varus or valgus mechanical alignment, or joint line obliquity, 2) a correlation between anatomic factors such as the femoral neck angle and the overall mechanical alignment will be present, 3) and there will be significant variation in the overall mechanical alignment and joint line obliquity between the lower extremities in the same subject, and in the ability of 2D images to predict the orientation measured on 3D images corrected for rotation.

Materials and Methods

One hundred healthy adults (200 knees) were recruited to participate in this Institutional Review Board-approved, cross-sectional study. From March 2011 to January 2012, subjects for the study were recruited from the orthopaedic outpatient clinics, and included family and friends of patients visiting the clinic, patients presenting with complaints unrelated to their lower extremities, and faculty and staff at our institution. Informed, written consent was obtained from each subject. Inclusion criteria were adults over the age of 18 years who have been verified via interview to be asymptomatic in both knees. Exclusion criteria were patients with a history of trauma, surgery, or symptoms in either of their knees or lower extremities, inflammatory arthritis, neuromuscular disorders, congenital anomalies, difficulty standing or walking independently, or pregnancy. The mean age of the subjects recruited was 35.5 ± 11.5 years, and consisted of 58 females and 42 males. Seventy-seven of the subjects were Caucasian, 13 African-American, and 10 Asian American. This is similar to the population of total knee patients in the total joint repository at our institution. Of 3245 total knee patients in which data is maintained, 64% were female, and 79% were Caucasian.

All subjects underwent standing, simultaneous anteroposterior (AP) and lateral imaging of the pelvis and bilateral lower extremities using the EOS® X-Ray Imaging Acquisition System (EOS Imaging Inc, Paris, France). The EOS® system uses two radiographic imaging acquisition systems mounted at right angles to each other within the apparatus, which allows simultaneous orthogonal imaging of the lower extremities. The floor of the imaging apparatus has a grid to ensure each patient's feet were consistently positioned, with the patellae facing forward. High-quality images are obtained through the use of a novel x-ray detector signal technique based on the principle of a multi-wire proportional chamber, which allows for substantial amplification of the x-ray signal. These images are obtained at a fraction of radiation exposure compared to conventional radiographic techniques: 800 to 1000 times less than CT imaging and 6 to 9 times less than conventional radiography (23, 24). An embedded software program (SterEOS ; EOS® Imaging Inc, Paris, France) uses the simultaneity and orthogonality of the frontal and lateral plane 2D images, to generate a 3D model of the underlying bony structures. This reconstruction technique has previously been described and validated in the diagnosis of scoliotic deformities and lower extremity torsional measurements (22, 23, 25).

After 3D parametric modeling, lower extremity rotation is controlled for via superimposition of the posterior condyles in the lateral view. Semi-automated identification of anatomic landmarks is performed, from which the hip-knee-ankle angle (HKA), mechanical lateral distal femoral angle (mLDFA), medial proximal tibial angle (MPTA), anatomical-mechanical angle (AMA), medial neck-shaft angle (MNSA), femoral bow, and tibial bow are calculated (definitions presented in Table 1) (22, 26). For convention, the HKA angle value was expressed as a deviation from 180° with a negative value for varus and positive value for valgus alignment. Prior to 3D parametric modeling and controlling for rotation, both the HKA and mLDFA were measured on the frontal, 2D images, for later comparison to the 3D values (Figure 1).

All 200 knees included in this study were individually characterized as being in varus (-3°), valgus (3°), or neutral ($0^\circ \pm 3^\circ$) alignment based on the HKA value. The mechanical lateral distal femoral angle was used to determine whether the native knee joint line was perpendicular to the mechanical axis of the femur (target $90^\circ \pm 3^\circ$) or whether joint line obliquity was present (mLDFA of 87° or 93°).

Statistical Analyses

Percentages and 95% confidence intervals (CIs), derived from 10000 Monte Carlo simulations, were calculated for the percentage of knees with a neutral, varus, or valgus alignment. Student's two-tailed t-tests were used to compare differences in radiographic parameters between male and female knees, with statistical significance set at a p-value of <0.05 .

Pearson's correlation coefficients were calculated, and graded using previously described semi-quantitative criteria, to determine the association between the radiographic parameters measured, and the overall mechanical alignment and presence of joint line obliquity (27).

Fischer's exact tests were used to determine if the correlation of overall mechanical alignment and joint line obliquity between the two lower extremities of the same subject, and between 2D and 3D images, were significant. Statistical significance was set at a p-value of <0.05 . The cohen's kappa coefficient (κ) was estimated, and graded using previously described semi-quantitative criteria, to determine the amount of agreement between the measurements, accounting for the probability of agreement simply by chance (28).

Source of Funding

No external funding was provided for this study.

Results

For measurements of the HKA angle across 200 knees, 70.0% were neutral (95% CI: 63.5%–76.5%), 19.5% in varus (95% CI: 14%–25%), and 10.5% in valgus (95% CI: 6.5%–12.5%). 32.1% of the male knees and 10.3% of the female knees were in a varus alignment, while 8.3% of the male knees and 12.1% of the female knees were in a valgus alignment. The absolute numbers of male and female knees in neutral, varus, or valgus alignment is presented in Table 2.

The mean mLDFA in all knees was $86.9^\circ \pm 1.7^\circ$, with a joint line obliquity of 3° present in 52.5% of all knees (95% CI: 45.5%–59.5%), and absent in 47.5% of all knees (95% CI: 40.5%–54.5%). 45.2% of male knees and 57.8% of female knees demonstrated joint line obliquity. The absolute numbers of male and female knees with joint line obliquity is presented in Table 3. Only 31% of all knees demonstrated both a neutral mechanical axis and the absence of joint line obliquity.

Overall, male knees possessed a more varus mechanical alignment with a mean HKA of $-1.49^\circ \pm 2.87^\circ$, versus $0.14^\circ \pm 2.34^\circ$ in female knees ($p < 0.001$). The MPTA was in more

varus in the male knees versus the female knees ($87.43^\circ \pm 2.72^\circ$ versus $88.75^\circ \pm 2.36^\circ$, $p < 0.001$). However, the mean mLDFA was more oblique in the female knees ($86.73^\circ \pm 1.84^\circ$ versus $87.2^\circ \pm 1.5^\circ$, $p = 0.04$). Lastly, the mean medial neck-shaft angle was more varus in the male subjects ($127.33^\circ \pm 4.24^\circ$ versus $128.94^\circ \pm 4.73^\circ$, $p = 0.01$). No significant difference was present for the other outcomes measured between the male and female subjects. Table 4 presents the mean values for each radiographic outcome, and whether a significant difference was present between the male and female knees.

Pearson's correlation coefficients demonstrated the mLDFA to have a fair/moderate inverse correlation with the HKA ($r = -0.52$), indicating that as the mLDFA decreased (more valgus joint line), the HKA value increased (indicating a more valgus overall alignment). In addition, the MPTA had a fair/moderate correlation with the HKA ($r = 0.57$), indicating that as the MPTA decreased (more varus proximal tibia), the HKA value also decreased (more varus overall alignment). The correlation of all other radiographic outcomes with the HKA was poor to low ($r = -0.13$ to 0.31). Furthermore, correlations were poor to low ($r = -0.28$ to 0.30) between the MPTA, AMA, MNSA, femoral bow, and tibial bow, with the presence of joint line obliquity (Table 5).

The agreement of the overall mechanical alignment in one lower extremity the other extremity was statistically significant, especially for knees with a neutral, mechanical alignment ($p < 0.001$). When the left knee is in a neutral mechanical alignment, the likelihood of the right knee also possessing a neutral HKA is 84.1%. This correlation decreases in the presence of a varus or valgus alignment. When the left knee is in varus, there is a 68.4% likelihood that the right knee will also be in varus, and when the left knee is in valgus, there is only a 41.7% likelihood that the right knee will also be in valgus. The Cohen's kappa coefficient was estimated to be 0.48 (95% CI: 0.3–0.66), which correlates with a “moderate” agreement between the two lower extremities in the same subject.

For the presence of joint line obliquity, the agreement between the lower extremities in the same subject was also statistically significant ($p < 0.001$). If joint line obliquity is present in the left knee, the right knee is 79.6% likely to also possess joint line obliquity. Similarly, if the left knee is absent of joint line obliquity, the right knee is also 66.7% likely to be absent of joint line obliquity. The Cohen's kappa coefficient was 0.46 (95% CI: 0.29–0.63), which again correlated with a “moderate” agreement between the two lower extremities in the same subject.

Comparisons of the HKA and mLDFA between the 2D images and the 3D images, provided a surrogate for the accuracy of a 2D, hip-to-ankle image in predicting the morphology seen on a 3D image corrected for rotation. The 2D and 3D radiographic measurements for HKA were highly correlated across the 200 knees imaged ($p < 0.001$). When the 2D image demonstrates a knee in neutral alignment, the corresponding 3D image is 92.9% likely to also be in neutral alignment. Furthermore, when the 2D image demonstrates a knee in valgus alignment, the corresponding 3D image is 100% likely to also be in a valgus alignment. However, when a 2D image demonstrates a knee in varus alignment, there is only a 75.0% likelihood that the 3D image will also demonstrate a varus alignment. Of the 44 cases in which the 2D image demonstrated a varus mechanical alignment, there were 11 cases in

which the corresponding 3D image did not demonstrate a varus alignment. The Cohen's kappa coefficient was estimated to be 0.77 (95% CI: 0.68–0.86), which correlates with a “substantial agreement” between the 2D and 3D images for overall, mechanical alignment (28). When a 2D measurement indicates the presence of joint line obliquity, the 3D measurement has an 85.3% probability of also demonstrating the presence of joint line obliquity. Of the 95 cases in which the 2D measurement demonstrated joint line obliquity, there were 14 cases in which the corresponding 3D image did not demonstrate joint line obliquity. When a 2D measurement indicates the absence of joint line obliquity, the 3D measurement has a 75.2% probability of also demonstrating the absence of joint line obliquity. Of the 105 cases in which joint line obliquity was absent on the 2D image, there were 26 cases in which the corresponding 3D image demonstrated joint line obliquity to be present. The Cohen's kappa coefficient was estimated to be 0.58 (95% CI: 0.47–0.69), which correlates with a “moderate agreement” between the 2D and 3D images for joint line obliquity.

Appendix

An additional table summarizing the measurement parameters for knees in a neutral, valgus, or varus alignment, and for male and female knees separately, is presented.

Discussion

Recently, the importance of restoration of a neutral mechanical alignment on both TKA survivorship and clinical function has been questioned (9, 10, 12, 13). Bellemans et al. have suggested that the goal of a neutral mechanical alignment may not be “normal” for a significant proportion of the population (10). However, full-length standing radiographs were used to obtain their morphometric measurements, which may be influenced by the rotational position of the lower extremities (10, 20, 21). The purposes of this study were to obtain 3D, weight-bearing, full-length lower extremity images corrected for rotation in asymptomatic adults, to establish 1) normative data of limb alignment and joint line orientation, 2) anatomic factors contributing to a varus or valgus alignment and the presence of joint line obliquity, 3) the degree of correlation for mechanical alignment and joint line obliquity between the lower extremities in the same subject, and 4) the capability of full-length 2-dimensional (2D) images to predict the orientation measured on 3D images corrected for rotation.

As in the study by Bellemans et al., a substantial fraction of knees in our study were not in a neutral, mechanical alignment, with 32.1% of male and 10.3% of female knees in varus, and 8.3% of male and 12.1% of female knees in a valgus. Furthermore, only 31% of all knees demonstrated both a neutral mechanical axis, and the absence of joint line obliquity, contributing additional support that restoration of a neutral mechanical axis with the femoral and tibial joint lines perpendicular to the mechanical axes, may not be “normal” for the majority of the population. Both the mL DFA and MPTA had a fair/moderate association with the HKA, but our data did not demonstrate a correlation between the HKA and the femoral bow, neck-shaft angle, or anatomic-mechanical angle, as presented by Bellemans et al. (10). These differences may be attributed to the use of 3D images corrected for rotation to

obtain our measurements, and also differences in the patient populations sampled. Furthermore, none of the radiographic outcomes measured, other than the HKA, were correlated with the mLDFA, thus also limiting their predictive capability for joint line obliquity. Therefore, the ability to use radiographic parameters such as the MNSA, AMA, and femoral or tibial bow to predict the presence of a constitutional varus or valgus alignment, or joint line obliquity remains limited.

In addition, it remains unclear how to reliably predict the normal mechanical axis and joint line alignment for patients who present with degenerative joint disease. Following implantation of a kinematically aligned TKA, it has been suggested that the surgeon can assess if the components are anatomically aligned if they match the angle of the joint line of the contralateral, normal knee (13). However, this study demonstrates that in asymptomatic adults, there is only a moderate level of agreement between the two lower extremities in the same subject for both the overall mechanical alignment and the presence of joint line obliquity. Thus, it remains unclear if the contralateral lower extremity can reliably be used to assess if the pre-arthritis alignment of the operative extremity has been achieved postoperatively.

Lastly, this study tried to establish if full-length, 2D images could accurately predict the lower extremity orientation measured on corresponding, 3D images corrected for rotation. For the HKA, the 2D and 3D images demonstrated a substantial amount of agreement based on the kappa coefficient. The greatest amount of agreement was present for knees in a neutral or valgus alignment (92.9% and 100% likelihood, respectively), with a decrease for knees in a varus alignment (75.0% likelihood). External rotation of the knee relative to the hip and the ankle could lead to a perceived constitutional varus alignment, thus contributing to the difference seen between the 2D and 3D images for lower extremities in varus (10). Similarly, there was a moderate agreement, based on the kappa coefficient, between the 2D and 3D images for the presence or absence of joint line obliquity. In this study, the rotational position of the lower extremities was controlled for by use of a foot grid in the imaging apparatus, and by positioning the patellae facing forward. Despite this attention to detail, differences were present between the 2D and 3D images for knees in a varus alignment, and in assessing the presence of joint line obliquity. Thus, whether rotationally controlled, 3D images are necessary to predict a patient's true limb morphology remains in question.

This study has several limitations, including the use of a single observer to perform the anatomic landmarking for the radiographic measurements, which may allow the introduction of systematic bias. However, this also ensures consistency in the measurements across the entire cohort. A second limitation is that this is an observational study of asymptomatic patients, and thus conclusions regarding alignment cannot be drawn for patients with degenerative joint disease who are candidates for total knee arthroplasty. However, despite these limitations, this study is important as it is the first to present normative data of limb alignment and joint line orientation in asymptomatic, healthy adults measured on 3D, weight-bearing, full-length images. Future directions should focus on the postoperative radiographic alignment achieved following total knee arthroplasty, and the effect of rotational control on the outcomes measured. Furthermore, studies should focus on whether restoration to a neutral, mechanical alignment and perpendicular joint line in TKA leads to

improved results versus leaving knees in slight varus or valgus. Recently, Vanlommel et al., in a review of 143 TKAs with a preoperative varus deformity, demonstrated better clinical and functional outcome scores in patients who were left in mild varus, versus those who were corrected to a neutral, mechanical axis (29). Thus, the importance of restoration to a neutral, mechanical axis in TKA continues to be an area in need of attention. In summary, our data demonstrates that 1) a substantial portion of adults possess a varus or valgus mechanical alignment and joint line obliquity, 2) the mechanical alignment and joint line orientation of one lower extremity does not necessarily match the contralateral lower extremity in the same subject, and 3) 2D images possess a limited degree of accuracy in predicting a varus mechanical alignment and the presence or absence of joint line obliquity seen in 3D, rotationally controlled images.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

References

1. Bourne RB, Chesworth BM, Davis AM, Mahomed NN, Charron KD. Patient satisfaction after total knee arthroplasty: Who is satisfied and who is not? *Clin Orthop Relat Res*. 2010 Jan; 468(1):57–63. [PubMed: 19844772]
2. Jones CA, Beaupre LA, Johnston DW, Suarez-Almazor ME. Total joint arthroplasties: Current concepts of patient outcomes after surgery. *Rheum Dis Clin North Am*. 2007 Feb; 33(1):71–86. [PubMed: 17367693]
3. Noble PC, Conditt MA, Cook KF, Mathis KB. The John Insall award: Patient expectations affect satisfaction with total knee arthroplasty. *Clin Orthop Relat Res*. 2006 Nov; 452:35–43. [PubMed: 16967035]
4. Longstaff LM, Sloan K, Stamp N, Scaddan M, Beaver R. Good alignment after total knee arthroplasty leads to faster rehabilitation and better function. *J Arthroplasty*. 2009 Jun; 24(4):570–578. [PubMed: 18534396]
5. Chao EY, Neluhani EV, Hsu RW, Paley D. Biomechanics of malalignment. *Orthop Clin North Am*. 1994 Jul; 25(3):379–386. [PubMed: 8028881]
6. Choong PF, Dowsey MM, Stoney JD. Does accurate anatomical alignment result in better function and quality of life? comparing conventional and computer-assisted total knee arthroplasty. *J Arthroplasty*. 2009 Jun; 24(4):560–569. [PubMed: 18534397]
7. Berend ME, Ritter MA, Meding JB, Faris PM, Keating EM, Redelman R, et al. Tibial component failure mechanisms in total knee arthroplasty. *Clin Orthop Relat Res*. 2004 Nov; 428:26–34. (428). [PubMed: 15534515]
8. Ritter MA, Faris PM, Keating EM, Meding JB. Postoperative alignment of total knee replacement: its effect on survival. *Clin Orthop Relat Res*. 1994 Feb; 299:153–156. (299). [PubMed: 8119010]
9. Parratte S, Pagnano MW, Trousdale RT, Berry DJ. Effect of postoperative mechanical axis alignment on the fifteen-year survival of modern, cemented total knee replacements. *J Bone Joint Surg Am*. 2010 Sep 15; 92(12):2143–2149. [PubMed: 20844155]
10. Bellemans J, Colyn W, Vandenuecker H, Victor J. The Chitranjan Ranawat award: Is neutral mechanical alignment normal for all patients? the concept of constitutional varus. *Clin Orthop Relat Res*. 2012 Jan; 470(1):45–53. [PubMed: 21656315]
11. Bellemans J. Neutral mechanical alignment: A requirement for successful TKA: Opposes. *Orthopedics*. 2011 Sep 9; 34(9):e507–e509. [PubMed: 21902146]
12. Howell SM, Hodapp EE, Vernace JV, Hull ML, Meade TD. Are undesirable contact kinematics minimized after kinematically aligned total knee arthroplasty? an intersurgeon analysis of consecutive patients. *Knee Surg Sports Traumatol Arthrosc*. 2012 Oct 2.

13. Howell SM, Howell SJ, Kuznik KT, Cohen J, Hull ML. Does a kinematically aligned total knee arthroplasty restore function without failure regardless of alignment category? *Clin Orthop Relat Res.* 2013 Mar; 471(3):1000–1007. [PubMed: 22996362]
14. Dossett HG, Swartz GJ, Estrada NA, LeFevre GW, Kwasman BG. Kinematically versus mechanically aligned total knee arthroplasty. *Orthopedics.* 2012 Feb 17; 35(2):e160–e169. [PubMed: 22310400]
15. Hungerford DS, Kenna RV, Krackow KA. The porous-coated anatomic total knee. *Orthop Clin North Am.* 1982 Jan; 13(1):103–122. [PubMed: 7063184]
16. Hus RW, Himeno S, Coventry MB, Chao EY. Normal axial alignment of the lower extremity and load-bearing distribution at the knee. *Clin Orthop Relat Res.* 1990 Jun;(255):215. (255).
17. Bellemans J, Carpentier K, Vandenuecker H, Vanlauwe J, Victor J. The john insall award: Both morphotype and gender influence the shape of the knee in patients undergoing TKA. *Clin Orthop Relat Res.* 2010 Jan; 468(1):29–36. [PubMed: 19669385]
18. Bardakos N, Cil A, Thompson B, Stocks G. Mechanical axis cannot be restored in total knee arthroplasty with a fixed valgus resection angle: A radiographic study. *J Arthroplasty.* 2007 Sep; 22 Suppl 2(6):85–89. [PubMed: 17823023]
19. Nam D, Maher PA, Robles A, McLawhorn AS, Mayman DJ. Variability in the relationship between the distal femoral mechanical and anatomical axes in patients undergoing primary total knee arthroplasty. *J Arthroplasty.* 2013 Feb 22.
20. Radtke K, Becher C, Noll Y, Ostermeier S. Effect of limb rotation on radiographic alignment in total knee arthroplasties. *Arch Orthop Trauma Surg.* 2010 Apr; 130(4):451–457. [PubMed: 19898854]
21. Jiang CC, Insall JN. Effect of rotation on the axial alignment of the femur. pitfalls in the use of femoral intramedullary guides in total knee arthroplasty. *Clin Orthop Relat Res.* 1989 Nov;(248): 50–56. (248). [PubMed: 2805495]
22. Chaibi Y, Cresson T, Aubert B, Hausselle J, Neyret P, Hauger O, et al. Fast 3D reconstruction of the lower limb using a parametric model and statistical inferences and clinical measurements calculation from biplanar X-rays. *Comput Methods Biomech Biomed Engin.* 2012; 15(5):457–466. [PubMed: 21229412]
23. Deschenes S, Charron G, Beaudoin G, Labelle H, Dubois J, Miron MC, et al. Diagnostic imaging of spinal deformities: Reducing patients radiation dose with a new slot-scanning X-ray imager. *Spine (Phila Pa 1976).* 2010 Apr 20; 35(9):989–994. [PubMed: 20228703]
24. Polkowski GG, Nunley RM, Ruh EL, Williams BM, Barrack RL. Does standing affect acetabular component inclination and version after THA? *Clin Orthop Relat Res.* 2012 Nov; 470(11):2988–2994. [PubMed: 22610527]
25. Buck FM, Guggenberger R, Koch PP, Pfirrmann CW. Femoral and tibial torsion measurements with 3D models based on low-dose biplanar radiographs in comparison with standard CT measurements. *AJR Am J Roentgenol.* 2012 Nov; 199(5):W607–W612. [PubMed: 23096205]
26. Paley, D.; Herzenberg, JE. Principles of deformity correction. 1st ed.. New York: Springer-Verlag; 2003.
27. Munro, BH. Statistical Methods for Healthcare Research. 3rd ed.. Lippincott-Raven; 1997. Correlation; p. 224–245.
28. Viera AJ, Garrett JM. Understanding interobserver agreement: The kappa statistic. *Fam Med.* 2005 May; 37(5):360–363. [PubMed: 15883903]
29. Vanlommel L, Vanlommel J, Claes S, Bellemans J. Slight undercorrection following total knee arthroplasty results in superior clinical outcomes in varus knees. *Knee Surg Sports Traumatol Arthrosc.* 2013 Apr 4.

Figure 1.
2D images demonstrating measurement of the A) hip-knee-ankle (HKA; -8.0°), B) mechanical lateral distal femoral angle (mLDFA; 86.2°), and C) medial proximal tibial angle (MPTA; 83.4°).

Table 1

Radiographic measurements performed on 3D, rotationally controlled images of each lower extremity.

Radiographic Measurement	Acronym	Definition
Hip-Knee-Ankle Angle (°)	HKA	Angle formed by the mechanical femoral axis and mechanical tibial axis
Mechanical Lateral Distal Femoral Angle (°)	mLDFA	Lateral angle formed between the mechanical femoral axis and the joint line of the distal femur
Medial Proximal Tibial Angle (°)	MPTA	Medial angle formed between the mechanical tibial axis and the knee joint line of the proximal tibia
Anatomical-Mechanical Angle (°)	AMA	The difference between the angles created by the anatomic axis of the femur and the distal femoral joint line, and the mechanical axis of the femur and the distal femoral joint line
Medial Neck-Shaft Angle (°)	MNSA	The angle formed by a line drawn through the center of the femoral shaft, and a line from the center of the femoral head through the center of the femoral neck
Femoral Bow (mm)	Not Applicable	The difference between the hip lateral offset and the femoral bow offset. The <i>hip lateral offset</i> was measured as the perpendicular distance (mm) between the center of the femoral head, and a line drawn through the center of the femoral shaft originating 10 cm below the tip of the lesser trochanter. The <i>femoral bow offset</i> was the perpendicular distance (mm) from the center of the femoral head, and the anatomic axis of the femur drawn from the center of the distal third of the femur above the knee (10cm above the most distal aspect of the femur).
Tibial Bow (mm)	Not Applicable	The perpendicular distance between the anatomic axis of the tibia and the center of the talus

Table 2

The absolute number and percentage of male and female knees in a neutral, valgus, or varus alignment, respectively.

	All (n=200)			Male (n=84)			Female (n=116)		
	Neutral	Valgus (3°)	Varus (-3°)	Neutral	Valgus (3°)	Varus (-3°)	Neutral	Valgus (3°)	Varus (-3°)
Frequency (absolute number)	140	21	39	50	7	27	90	14	12
Percentage	70	10.5	19.5	59.5	8.3	32.1	77.6	12.1	10.3

The absolute number and percentage of male and female knees with a joint line obliquity of 3° based on measurement of the mL DFA.

Table 3

	All (n=200)		Male (n=84)		Female (n=116)	
	Obliquity Absent	Obliquity Present	Obliquity Absent	Obliquity Present	Obliquity Absent	Obliquity Present
Frequency (absolute number)	95	105	46	38	49	67
Percentage	47.5	52.5	54.8	45.2	42.2	57.8

Table 4

A comparison of the mean radiographic measurement values between the male and female subjects. All values are presented as the mean $\pm$ standard deviation. Statistically significant differences are highlighted.

Radiographic Parameter	Male (n=84)	Female (n=116)	p-value
HKA (°)	-1.49 ± 2.87	0.14 ± 2.34	<0.001
mLDFA (°)	87.20 ± 1.50	86.73 ± 1.84	0.04
MPTA (°)	87.43 ± 2.72	88.75 ± 2.36	<0.001
AMA (°)	4.65 ± 1.11	4.43 ± 1.16	0.17
MNSA (°)	127.33 ± 4.24	128.94 ± 4.73	0.01
Femoral Bow (mm)	-0.02 ± 3.08	0.52 ± 3.08	0.22
Tibial Bow (mm)	0.35 ± 2.06	0.61 ± 1.63	0.35

Table 5

Pearson's correlation coefficients calculated to determine the association of each radiographic parameter with the overall mechanical alignment (HKA), and the presence of joint line obliquity (mLDFA).

Radiographic Parameter	Mechanical Alignment HKA (°)	Joint Line Obliquity mLDFA (°)
HKA (°)	1.00	−0.52
mLDFA (°)	−0.52	1.00
MPTA (°)	0.57	−0.03
AMA (°)	−0.13	0.30
MNSA (°)	0.09	−0.24
Femoral Bow (mm)	0.01	−0.28
Tibial Bow (mm)	0.31	−0.02