abstract

The purposes of this study were (1) to compare lower limb alignment measurements between radiographs and computer-assisted surgery and (2) to evaluate the discrepancy in lower limb alignment between computer-assisted surgery with a high tibial osteotomy protocol and computer-assisted surgery with a total knee arthroplasty (TKA) protocol in the same knee. Seventy-one TKAs were performed on patients with primary osteoarthritis using computer-assisted surgery. Preoperative lower limb alignment was measured using the mechanical axis during bipedal, weight-bearing, whole-leg anteroposterior radiography (measure 1). The intraoperative mechanical axis was measured with computer-assisted surgery according to the high tibial osteotomy protocol before joint exposure (measure 2). After changing the software and joint exposure, the intraoperative mechanical axis was measured with computer-assisted surgery according to TKA protocol (measure 3). After final TKA implantation, the lower limb mechanical axis was measured with computer-assisted surgery following the TKA protocol (measure 4). Postoperative lower limb alignment was measured using the mechanical axis on whole-leg standing anteroposterior radiographs (measure 5). The mechanical axis and median value from each group were compared. Factors affecting the mechanical axis measurement were also analyzed. The difference in the mechanical axis between measures 1 and 2, measures 1 and 3, and measures 2 and 3 was significant ($P<.0001$, $.<.0001$, and $.=0.0007$, respectively). The difference between measures 4 and 5 was also significant ($P<.0001$). Factors affecting the mechanical axis measurement, such as age, height, weight, and range of motion, showed no correlation ($R^2=0.07244$ and adjusted $R^2=0.01622$). The pre- and postoperative radiological measurements of limb alignment using the mechanical axis were different from the intraoperative measurements with navigation.
It is well known that an accurate lower limb alignment is important to improve the outcome of total knee arthroplasty (TKA). Several methods are used to measure the mechanical axis pre- and postoperatively. The simple radiograph is the most cost-effective tool for the measurement of lower limb deformity. However, lower limb alignment may be over- or underestimated due to weight-bearing status when using a long-leg standing radiograph because osteoarthritic knees have chondral or osteochondral defects, which can cause space narrowing.

Navigated measurements of the mechanical axis of the lower limb are accurate and reproducible. Navigation systems have several protocols to measure the mechanical axis. Navigation systems using a TKA protocol perform bony landmark registration directly from the bone surface. Navigation systems using a high tibial osteotomy (HTO) protocol perform registration from the skin surface before joint exposure and may obtain the wrong information due to soft tissue thickness. Recently, many studies have demonstrated an improved mechanical axis alignment with the use of navigation systems. However, some studies have found that navigation procedures do not demonstrate an improved alignment due to their own complications. To the authors’ knowledge, no publications exist regarding the comparison of measurements of lower limb alignment between the TKA protocol and HTO protocol.

The purposes of this study were (1) to compare lower limb alignment measurements between radiographs and computer-assisted surgery and (2) to evaluate the discrepancy in lower limb alignment between computer-assisted surgery with an HTO protocol and with a TKA protocol in the same knee. The authors hypothesized that the mechanical axis of lower limbs measured using TKA and HTO protocols is different and that the mechanical axis measured from radiographs and navigation systems are different.

**Materials and Methods**

**Patients and Study Design**

Between May and October 2011, seventy-one TKAs (4 men, 67 women) were performed on patients with primary osteoarthritis using computer-assisted surgery. Knees that were severely deformed, ankylosed, or unstable or had inflammatory arthritis were excluded. Severely deformed knees were defined as those with more than 10° of a coronal deformity of the mechanical axis measured on bipedal, weight-bearing, whole-leg anteroposterior (AP) radiographs and more than 10° of flexion contracture and more than 5° of hyperextension on physical examination. Unstable knees were defined as those with more than 3 mm of medial laxity in varus and more than 5 mm of medial laxity in valgus on stress radiographs compared with the contralateral side.

Patients’ mean height was 155.7 cm, mean weight was 60.8 kg, and mean range of motion of the involved knee was 123.1° (Table 1). Preoperative lower limb alignment was measured as mechanical axis with bipedal, weight-bearing, whole-leg AP radiographs (measure 1). The mechanical axis was measured intraoperatively using navigation according to an HTO protocol before joint exposure (measure 2). After changing the software and joint exposure, calculation of the intraoperative mechanical axis was repeated using navigation with a TKA protocol for the same patient (measure 3). After the final TKA implantation, the final lower limb mechanical axis was measured using navigation following the TKA protocol (measure 4). Postoperative lower limb alignment was measured as the mechanical axis using bipedal, weight-bearing, whole-leg AP radiographs (measure 5); each measure was compared, and factors affecting the difference were analyzed.

**Surgical Technique**

**Measurement of Mechanical Axis With Navigation**

All cases were performed by a single surgeon (S.-S.S.). The imageless OrthoPilot navigation system (B. Braun Aesculap, Tuttingen, Germany) was used in all cases. The camera was positioned 2 meters away from the patient. Before joint exposure, optical navigation trackers using navigation with an HTO protocol (OrthoPilot HTO 1.5; B. Braun Aesculap) were rigidly attached to the femur and tibia. Then, the center of rotation of the hip, knee, and ankle were defined following a prescribed procedure, and specific landmarks of the knee were digitized using a navigation pointer (Figure 1). With this information, preoperative lower limb mechanical axis was measured. After performing the midline skin incision and a medial parapatellar arthrotomy with navigation following TKA protocol (OrthoPilot TKA 4.3; Aesculap), the center of rotation of the hip, knee, and ankle were defined and the registration process was performed (Figure 2). Again, the preoperative lower limb mechanical axis was measured.

Using bone surface information obtained during registration, an adapted bone

---

**Table 1**

Demographic Data (N=71)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Data a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sex</td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>4 (5.6%)</td>
</tr>
<tr>
<td>Female</td>
<td>67 (94.4%)</td>
</tr>
<tr>
<td>Age, y</td>
<td>69.5±6.1 (55-84)</td>
</tr>
<tr>
<td>Weight, kg</td>
<td>60.8±11.6 (39-100)</td>
</tr>
<tr>
<td>Height, cm</td>
<td>155.7±6.1 (134-165)</td>
</tr>
<tr>
<td>BMI, kg/m²</td>
<td>25.1±4.2 (16-40)</td>
</tr>
<tr>
<td>Flexion contracture, deg</td>
<td>5.10±8.91 (0-52)</td>
</tr>
<tr>
<td>Flexion, deg</td>
<td>127.97±10.77 (90-145)</td>
</tr>
<tr>
<td>Range of motion, deg</td>
<td>123.11±15.57 (70-145)</td>
</tr>
</tbody>
</table>

Abbreviations: BMI, body mass index; deg, degrees.

aValues are shown as mean±SD (range) or n (%) where appropriate.
model was created. The cutting block was oriented to the bone using real-time visualization from the navigation system. The tibial resection was performed, followed by distal femoral resection. At each step of the operation, the surgeon checked the ligamentous tension. After inserting the trial implants, the axis of the leg, the range of motion, and the stability of the joint were examined and evaluated. When the trials revealed optimal position and balance, they were removed and the real implants were cemented into place. Then, the final lower limb mechanical axis was measured with navigation.

Radiographic Measurement of the Mechanical Axis

In all patients, bipedal, weight-bearing, whole-leg AP radiographs were taken preoperatively and 3 weeks postoperatively. Lower limbs were fully extended, allowing the patella to face forward and both lateral malleoli to be 30 cm apart. Radiographs were taken with graduated-grid 30×90-cm cassettes at a distance of 1.8 m. To determine the mechanical axis, the angle between a line connecting the center of the femoral head to the center of the knee (highest point of intercondylar notch) and a line connecting the center of the knee (center between the medial and lateral tibial spine) to the center of the ankle (midline between the medial and lateral malleolus) was preoperatively measured. Postoperatively, the same landmarks were used as the hip and ankle center, but the centers of the femoral and tibial components were also used. Radiographic measurements were performed using the M-view version 5.4.8.2 picture archiving and communication system (Marotech, Seoul, Korea) by an independent observer (J.-H.S., Y.-J.K.) who was not involved in the measurements with the navigation system.

Statistical Analysis

The descriptive data are presented as mean±SD and range of minimum to maximum. Data were analyzed using the Wilcoxon signed rank test for comparison of each group. Multiple linear regressions were used for analyzing the factors affecting the differences in mechanical axis between each group. The results of regression analysis were reported as $R^2$ and adjusted $R^2$. Differences between groups were considered statistically significant if the 2-tailed $P$ values were less than .05. SPSS version 19 statistical software (SPSS Inc, Chicago, Illinois) was used for the statistical analyses.

RESULTS

Demographic data showed that patients with less deformed knees had a good range of motion and that a large number of women were included in the study (Table 1). The preoperative radiographic mechanical axis was different from measured values obtained with navigation regardless of whether the HTO protocol or TKA protocol was used ($P<.0001$ for both). The mechanical axis measured with navigation showed less varus deformity than that measured with radiography. The difference in the median value of the mechanical axis between HTO and TKA protocols was 1°; this was statistically significant ($P=.0007$). The mechanical axis measured with the HTO protocol showed more varus than that for the TKA protocol. Postoperative median value of the mechanical axis measured with navigation showed less varus than that measured with postoperative radiographs ($P<.0001$). The median value of the mechanical axis obtained from radiography showed greater malalignment than the mechanical axis measured with navigation (Table 2).

Factors affecting the differences in mechanical axis between each group, such as age, weight, height, and range of motion, were analyzed using multiple linear regression. Such factors were
poorly correlated with but also could not explain the differences between groups 1 and 2, groups 1 and 3, and groups 2 and 3 (R²=.0888, .0690, and .0437, respectively) (Tables 3-5).

**Discussion**

The current results showed limb alignments measured on bipedal, weight-bearing, whole-leg AP radiographs were different from limb alignment measured with navigation pre- and postoperatively. Several reasons exist for those differences. Long-leg standing AP radiographs were taken under weight-bearing conditions. On the contrary, computer-assisted surgery was performed in a nonweight-bearing supine position. Therefore, the weight-bearing condition might accentuate the degree of joint deformity. Patients with osteoarthritis usually have flexion, varus, and rotational deformity, which may cause apparent changes in the coronal plane, such as increased varus in internal rotation and increased varus in external rotation. In this study, every effort was made to take the radiograph in a neutral limb position for the purpose of lessening these biases. The limb alignment measurements on radiographs were performed with digital film on an LCD monitor instead of line drawing and goniometer on the radiograph, which might result in misalignment of limb alignment. A more pronounced difference in the mechanical axis was found on the preoperative measurement than on the postoperative measurement. In cases of soft tissue imbalance, the mechanical axis could be overestimated because of weight bearing during the long-leg standing AP radiograph. According to Bae et al, a varus of 9.5°±3.4° was found using preoperative radiographic measurement of the mechanical axis and a varus of 8.8°±2.6° was found using navigational measurement of mechanical axis during opening-wedge HTO. Their results showed moderate correlation between radiographic and navigational measurements (r=0.679). The current data showed a similar correlation (r=0.6184, data not shown). Furthermore, the correction of bony deformity via surgery decreased the effect of weight bearing on alignment measurement.

The difference in measurement of limb alignment between HTO and TKA protocols in the same patient was significant. Comparing preoperative radiographic limb alignment with that of the TKA protocol showed a more pronounced difference than comparing with the HTO protocol. To the authors’ knowledge, no other publications about this subject are available. Registration methods in HTO and TKA protocols are similar except for the knee joint registration. In the HTO protocol, knee joint registration is made on the soft tissue over the patella, both femoral epicondyles, and both tibial condyles instead of directly on bony landmarks. However, knee joint registration in the TKA protocol is made on the center of intercondylar notch, both of the femoral epicondyles, and the center of articular surface of both tibial plateaus. These differences in registration likely caused the

---

**Table 2**

| Measure | Median (95% CI) | Interquartile Range | P
|---------|----------------|--------------------|---
| 1       | 8.50 (7.50 to 9.89) | 6.5000 to 12.1500 | –
| 2       | 5.00 (4.77 to 7.00)  | 3.0000 to 7.7500  | <.0001
| 3       | 4.00 (3.00 to 6.23)  | –0.7500 to 7.0000 | <.0001
| 4       | 0.00 (0.00 to 1.00) | –1.0000 to 2.0000 | –
| 5       | 2.20 (1.50 to 2.90) | 0.7250 to 3.6500  | <.0001

Abbreviation: CI, confidence interval.

| Measure | Median (95% CI) | Interquartile Range | P
|---------|----------------|--------------------|---
| 1       | 8.50 (7.50 to 9.89) | 6.5000 to 12.1500 | –
| 2       | 5.00 (4.77 to 7.00)  | 3.0000 to 7.7500  | <.0001
| 3       | 4.00 (3.00 to 6.23)  | –0.7500 to 7.0000 | <.0001
| 4       | 0.00 (0.00 to 1.00) | –1.0000 to 2.0000 | –
| 5       | 2.20 (1.50 to 2.90) | 0.7250 to 3.6500  | <.0001

Abbreviation: CI, confidence interval.

---

**Table 3**

<table>
<thead>
<tr>
<th>Independent Variable</th>
<th>Coefficient (β)</th>
<th>SE</th>
<th>t Value</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, y</td>
<td>0.0879</td>
<td>0.0956</td>
<td>0.920</td>
<td>.3612</td>
</tr>
<tr>
<td>Height, cm</td>
<td>–0.1892</td>
<td>0.1043</td>
<td>–1.814</td>
<td>.0743</td>
</tr>
<tr>
<td>Weight, kg</td>
<td>0.0374</td>
<td>0.0543</td>
<td>0.689</td>
<td>.4935</td>
</tr>
<tr>
<td>Range of motion, deg</td>
<td>–0.0430</td>
<td>0.0363</td>
<td>–1.186</td>
<td>.2399</td>
</tr>
</tbody>
</table>

Abbreviations: deg, degrees; SE, standard error.

*Constant: 30.3033.

Note: R²=0.0888, adjusted R²=0.0327.
This study had several limitations. No power analysis was performed to verify the hypothesis, so the authors do not know how many samples are needed. Although radiography was controlled with strict protocols, some doubt exists about the consistency of radiographic measurement and the precision of radiographs. The authors avoided this bias by discarding unacceptable radiographs. An observational bias exists regarding the limb alignment measurement using radiography because the observer who was blinded to the navigational results also measured the mechanical axis. Computer-assisted surgery was performed by a single surgeon. Operator accidents are possible with respect to alignment measurement to correct mechanical axis during computer-assisted surgery.

### Conclusion

Pre- and postoperative weight-bearing radiologic measurement of limb alignment as a median value of mechanical axis are different from nonweight-bearing intraoperative measurements using navigation. Radiographic limb alignment showed a greater accentuated deformity than that of navigated measurements in the same patient. Different navigational protocols for measuring the mechanical axis give statistically different results, although the difference is only 1°. In this study, age, height, weight, and range of motion did not affect the difference in the measurement of lower limb alignment and could not explain any differences. Further studies are needed to analyze factors affecting the differences in limb alignment.

### References


---

**Table 4**

Factors Affecting Difference in Lower Limb Alignment Between Measures 1 and 3 (N=71)

<table>
<thead>
<tr>
<th>Independent Variable</th>
<th>Coefficient (β)</th>
<th>SE</th>
<th>t-value</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, y</td>
<td>0.1379</td>
<td>0.1029</td>
<td>1.340</td>
<td>.1849</td>
</tr>
<tr>
<td>Height, cm</td>
<td>-0.1006</td>
<td>0.1123</td>
<td>-0.896</td>
<td>.3738</td>
</tr>
<tr>
<td>Weight, kg</td>
<td>-0.0238</td>
<td>0.0585</td>
<td>-0.407</td>
<td>.6856</td>
</tr>
<tr>
<td>Range of motion, deg</td>
<td>-0.0053</td>
<td>0.0390</td>
<td>-0.135</td>
<td>.8933</td>
</tr>
</tbody>
</table>

**Table 5**

Factors Affecting Difference in Lower Limb Alignment Between Measures 2 and 3 (N=71)

<table>
<thead>
<tr>
<th>Independent Variable</th>
<th>Coefficient (β)</th>
<th>SE</th>
<th>t-value</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, y</td>
<td>0.0500</td>
<td>0.0788</td>
<td>0.635</td>
<td>.5274</td>
</tr>
<tr>
<td>Height, cm</td>
<td>0.0886</td>
<td>0.0859</td>
<td>1.031</td>
<td>.3064</td>
</tr>
<tr>
<td>Weight, kg</td>
<td>-0.0612</td>
<td>0.0448</td>
<td>-1.367</td>
<td>.1763</td>
</tr>
<tr>
<td>Range of motion, deg</td>
<td>0.0377</td>
<td>0.0299</td>
<td>1.263</td>
<td>.2110</td>
</tr>
</tbody>
</table>

Abbreviations: deg, degrees; SE, standard error.

---

Differences in limb measurements. Other possible causes of these differences are measurement errors. In this study, the TKA protocol was performed after the HTO protocol in all cases. Experience in limb alignment measurement with the HTO protocol before the TKA protocol may cause differences in the measurement of the mechanical axis. Although the difference in the mechanical axis between the HTO and TKA protocols was statistically significant, the median value of difference was only 1°, and its clinical significance should have been less important.

Many constitutional factors affect measurement of limb alignment, such as age, weight, height, and knee range of motion preoperatively. In total hip arthroplasty studies, significant registration errors occur in obese patients due to soft tissue thickness. Other studies showed that patients with a higher body mass index had a stronger correlation to registration errors. Such factors were analyzed with multiple linear regressions for the purpose of explaining preoperative differences in limb alignment between radiographic and navigational measurements. Preoperative factors such as age, weight, height, and knee range of motion were poorly correlated with limb alignment but also could not explain the differences between measures 1 and 2, measures 1 and 3, measures 2 and 3 (R²=0.0888, 0.0690, and 0.0437, respectively). From this result, the authors speculate that other factors affected the differences in limb alignment in addition to age, weight, height, and knee range of motion. Thus, it is possible that factors affecting the differences in limb alignment are multifactorial.


