Minimally invasive and robot-assisted procedures have potential advantages when used for total knee arthroplasty (TKA). The purpose of this cadaveric study was to examine whether robot-assisted minimally invasive procedures improve TKA alignment after modifying the robotic techniques and instruments.

Total knee arthroplasties were performed on 10 pairs of fresh cadaveric femora. Ten knees were replaced using the robot-assisted minimally invasive technique and 10 using the conventional minimally invasive technique. After prosthesis implantation, limb and prosthesis alignments were investigated by measuring mechanical axis deviation, femoral and tibial sagittal and coronal inclination, and femoral rotational alignment with 3-dimensional computed tomography scans. Postoperative alignment accuracy of the implanted prostheses was better in the robot-assisted minimally invasive TKA group than in the conventional minimally invasive TKA group as judged by the rotational alignment of the femoral component (0.7° ± 0.3° vs 3.6° ± 2.2°, respectively) and the tibial component sagittal angle (7.8° ± 1.1° vs 5.5° ± 3.6°, respectively). One sagittal inclination outlier for the tibial side existed in the robotic minimally invasive TKA group, and 2 outliers for the mechanical axis, 2 for the tibial side sagittal inclination, and 2 for the femoral rotational alignment existed in the conventional minimally invasive TKA group.

Higher implanted prostheses accuracy and fewer outliers in postoperative radiographic alignments can be attained with robot-assisted TKA. Minimally invasive TKA in combination with an improved robot-assisted technique is an alternative option to compensate for the shortcomings of conventional minimally invasive TKA.
Minimally invasive total knee arthroplasty (TKA) has gained much attention in recent years. Comparisons with conventional TKA have shown that minimally invasive TKA leads to shorter rehabilitation time, greater quadriceps muscle strength, and improved function, which prompted more widespread use of the technique.\textsuperscript{1,2} However, minimally invasive techniques have drawn criticism for potentially increasing the risk of component malalignment because of decreased knee joint exposure and increased technical difficulty of the surgery.\textsuperscript{3,4} Malposition of TKA affects implant fixation and leads to an increased risk of loosening, instability, and early knee prosthesis failure.\textsuperscript{5,6}

To further improve the accuracy of implant selection and position, alignment, and bone resection, robotic systems have been developed for TKA.\textsuperscript{7,8} Although knee robotic systems are not yet universally accepted, several investigators have demonstrated that robot-assisted TKA has the advantages of more accurate alignment, fewer outliers, and more accurate preoperative planning when compared with conventional TKA.\textsuperscript{7,9} However, no studies to date have investigated the outcomes of minimally invasive TKA using a robot-assisted procedure. The robot-assisted technique requires modifications in terms of fixation method, digitizing tools, and bone-cutting procedures.

The authors of this study hypothesized that minimally invasive TKA using a modified robot-assisted technique would provide better lower limb alignment and component orientation than conventional minimally invasive TKA. To test this hypothesis, they quantitatively compared radiologic outcomes of robot-assisted minimally invasive TKA with those of the conventional minimally invasive TKA using 3-dimensional (3-D) computed tomography (CT) in a human cadaveric model.

**Materials and Methods**

Total knee arthroplasties were performed on 10 pairs of fresh cadaveric femora. Ten knees were replaced using the robot-assisted minimally invasive technique and 10 using the conventional minimally invasive technique. The ORTHODOC system (Curexo, Inc, Seoul, South Korea) was used for the robot-assisted TKA. NexGen cruciate-retaining total knee prostheses (Zimmer, Warsaw, Indiana) with fixed bearings were used in all knees. A Bright Speed Edge WCT 440-140 apparatus (GE OEC Medical Systems, Inc, Warsaw, Indiana) equipped with an 8-channel scanner was used for 3-D CT scanning.

Preoperatively, a whole leg was scanned to generate a 3-D image from the femoral head through the knee joint to the ankle joint. The following 3 volumes were required for preoperative planning of ORTHODOC: femoral head, knee joint, and ankle joint (Figure 1). The CT scans provide ORTHODOC with input to create 3-D surface model images of the bone for computerized templating. After transferring the CT data to ORTHODOC, the surgeon (Y.-W.M.) chose the type and size of the components and the polyethylene from the available menus and positioned them freely via mouse control with the ORTHODOC software (Figure 2).

The height of the joint line, the varus–valgus alignment of the components in the frontal plane, their slope in the sagittal plane, and their rotation in the transversal plane were set individually in increments as low as 0.1° or 0.1 mm, as desired. The mechanical axis was set to 0°, and the tibial and femoral components were aligned perpendicular to the mechanical axis in the coronal plane. The positive value of the measured mechanical-axis
deviation pertained to the varus, and the negative meant the opposite. In the sagittal plane, the posterior slope of the tibial components was set to 7°, and the slope of the femoral components was set by case. In the transverse plane, the external rotation of the femoral components was set by case in relation to the transepicondylar axis. The rotation of the tibial components was then aligned with the rotation of the femoral component. The final position of the virtual components was transferred to the control unit of the robot.

**Surgical Technique**

A midline skin incision was made with a mean length of 10.5 cm. A mini-medial parapatellar approach to the knee joint was used. The knee was flexed and fixed with 2 clamps and 4 screws (Figure 3). The surgeon oriented the robot by guiding the digitizing probe to specific locations on the bone surface. The robot probed the registration markers in the femur and tibia using modified digitizing tools without an additional skin incision to match the CT images with reality (Figure 4). When the surface registration was completed, the surgeon digitized the motion recovery posts to ensure that the procedure could be resumed in the event that bone motion occurred. The surgeon replaced the digitizing probe with a cutter and guided the milling cutter to a position near the distal femur. The robot then milled the femoral volumes with a high-speed milling tool attached to its arm. After completing the femoral procedure, the surgeon guided the milling cutter to a position near the proximal tibia and performed tibial cutting through the same method.

To optimize the milling process under limited exposure, a new cutting device and tissue-sparing tunneling method were developed. The diameter of the cutter was decreased from 7.8 to 4 mm, and only 1 type of cutter was used in the femur and the tibia. The tissue-sparing tunneling method modified the cutting pathway and cutting steps for the minimally invasive surgery. In the femur, the new cutting device approached the bone horizontally, allowing a safe remnant bone margin and protection of the surrounding soft tissue (Figure 5). In the tibia, the cutter approached from a medial direction to avoid patellar tendon injury during bone cutting (B).

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**Figure 3:** Intraoperative photograph of conventional minimally invasive total knee arthroplasty showing the knee flexed and fixed by 6 clamps and 6 screws with an additional skin incision (A). Intraoperative photograph of robot-assisted minimally invasive total knee arthroplasty showing the knee fixed by 2 clamps and 4 screws with no additional skin incision (B).

**Figure 4:** A conventional digitizing probe (A) was modified into a needle probe (B) to be used with no further skin incision (C). This probe has modularity and includes extender joint and compatible ball tips (D).

**Figure 5:** A tissue-sparing tunneling method was developed for minimally invasive total knee arthroplasty. In the femur, a cutter approached the bone horizontally, allowing a safe remnant bone margin and protection of the surrounding soft tissue (A). In the tibia, the cutter approached from a medial direction to avoid patellar tendon injury during bone cutting (B).
femur started from the anterior chamfer cut, and a medial distal cut was followed by a lateral distal cut, changing the direction and posterior cut sequentially. After the bone preparation of the femur and tibia was completed, trial implants were placed, and the soft tissues were balanced as usual. Finally, components were inserted manually.

Radiographic Evaluation

Limb and prosthesis alignments in the coronal plane were investigated by measuring the medial mechanical femorotibial angle,\textsuperscript{10} femoral component medial angle,\textsuperscript{11} and tibial component medial angle\textsuperscript{11} via 3-D CT scans after prostheses implantation (Figure 6). Rotational alignment of the femoral component was evaluated with CT scans in relation to the transepicondylar axis (Figure 7). The femoral component sagittal angle was defined as the angle between the perpendicular line running proximally from the distal femoral surface in contact with the femoral component and the mechanical axis of the femur in the sagittal plane. The tibial component sagittal angle was defined as the angle between the undersurface of the tibial tray and the anatomical axis of the tibia in the sagittal plane.\textsuperscript{12} The outcome was defined as acceptable when within 3° and as an outlier when more than 3° from optimum.

RESULTS

Radiographic results of robot-assisted minimally invasive TKA and conventional minimally invasive TKA are summarized in the Table. Significant differences existed in the accuracy of postoperative radiographic alignment of implanted prostheses as judged by the rotational alignment of the femoral component (7.8°±1.1° vs 5.5°±3.6°, respectively [\(P=.010\)]) and the tibial component sagittal angle (0.7°±0.3° vs 3.6°±2.2°, respectively [\(P=.027\)])).

One sagittal inclination outlier for the tibial side existed in the robot-assisted minimally invasive TKA group, and 2 outliers for the mechanical axis, 2 for the tibial side sagittal inclination, and 2 for the femoral rotational alignment existed in the conventional minimally invasive TKA group.

The intraclass correlation coefficients of inter- and intraobserver variabilities were .83 and .88, respectively, when calculated with all measurements.

DISCUSSION

Minimally invasive and robot-assisted surgeries have potential advantages when used for TKA. Minimally invasive approaches may lead to decreased blood loss, decreased hospitalization time, quicker postoperative rehabilitation, and better functional outcomes.\textsuperscript{13-15} However, minimally invasive techniques may also result in component malalignment as a result of decreased visibility.\textsuperscript{13,14} However, robot-assisted techniques can contribute to greater accuracy of component position and joint alignment.\textsuperscript{16-18}

Although individual studies using a minimally invasive technique or a robot-assisted technique alone have been performed in vivo, no studies report the outcomes after merging these 2 technologies. If a surgeon lacks experience with robot-assisted and minimally invasive procedures, it is not easy to undertake this type of surgery. Although research involving a small number of fresh cadavers is not the
same as in vivo surgical practice, a cadaveric study is necessary to provide surgeons with appropriate training and to help them gain confidence in the use of the robotic system.

In the current study, a significant improvement occurred in 2 of the 6 radiological parameters for alignment of the components using robot-assisted minimally invasive TKA compared with conventional minimally invasive TKA. The reduction in the number of outliers for the various radiographic parameters was also important. The number of outliers decreased in the robot-assisted minimally invasive TKA group despite the fact that the surgeons were more experienced and familiar with conventional TKA than with robot-assisted TKA.

Consensus is growing that specialization instruments and surgical techniques should be designed to facilitate minimally invasive surgery.19-21 The current study also aimed to examine whether robot-assisted minimally invasive procedures can improve TKA alignment after modifying the robotic techniques and instruments. The modifications for minimally invasive surgery focused on fixation method, digitizing tools, and bone-cutting procedures. In terms of fixation method, the knee was fixed with 6 clamps and 6 screws with an additional skin incision in the conventional minimally invasive TKA group and with 2 clamps and 4 screws with no additional skin incision to reduce soft tissue violation in the robot-assisted minimally invasive TKA group. In terms of digitizing tools, the conventional probe was converted to a modular needle probe, which included an extender joint and ball tip. By using the needle probe, registration with no further skin incision became possible. The extender joint was developed to maintain compatibility of ball tips used during the calibration process.

Bone-cutting procedures were also modified for minimal invasiveness and were defined as a tissue-sparing tunneling method. This new technique has 3 main characteristics. First, bone-cutting steps were modified to minimize the incision length. Second, when cutting the bone, the cutter device was positioned inside the bony outer margin to protect important soft tissues, such as the medial collateral ligament, patellar tendon, and posterior capsule. Third, the cutting approach was modified. In the femur, the cutting device was addressed to the bone vertically to the cutting surface in the conventional minimally invasive TKA group and horizontally in the minimally invasive robot-assisted minimally invasive TKA group. In the tibia, the cutting device was addressed from the center in the conventional minimally invasive TKA group and from the medial direction to avoid patellar tendon injury in the robot-assisted minimally invasive TKA group.

Issues with robot-assisted minimally invasive TKA are relative morbidity, additional operative time, pain due to large markers and jigs, and ease of use and learning curve. Operative time required by the robot-assisted minimally invasive TKA is longer. Song et al18 reported a mean operative time 25 minutes longer than conventional minimally invasive TKA, but no increase in the short-term complication rate was reported. A high complication rate has been reported to be related to markers and jigs in early cases of robot-assisted minimally invasive TKA.16,17 Park and Lee17 reported fewer of these problems after switching to smaller markers and jigs, and no major adverse events were observed after completion of the learning process.

Robot-assisted minimally invasive TKA is technically demanding and has been reported to require a long learning curve. Song et al18 reported having experience with more than 150 cases prior to their study, and after completion of the learning process, major adverse events disappeared. Park and Lee17 experienced no soft tissue or fracture complications after completing half of their cases. However, it is debatable whether the learning period for robot-assisted minimally invasive TKA is longer than that of conventional minimally invasive TKA. Rees et al22 reported that a benefit in the use of the robot is a shorter learning curve for surgeons, especially those in the early stages of the learning curve.

The current study had some limitations. First, due to the nature of the ca-

### Radiologic Results of Robot-assisted and Conventional MIS TKA

<table>
<thead>
<tr>
<th>Angle</th>
<th>Robot-assisted MIS TKA</th>
<th>Conventional MIS TKA</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medial mechanical femorotibial</td>
<td>0.2±1.1</td>
<td>–0.5±2.8</td>
<td>.611</td>
</tr>
<tr>
<td>(−1.4 to 1.9)</td>
<td>(−3.2 to 3.8)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Femoral component coronal</td>
<td>90.3±1.0</td>
<td>90.5±1.2</td>
<td>.891</td>
</tr>
<tr>
<td>(88.8 to 91.7)</td>
<td>(88.4 to 92.3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tibial component coronal</td>
<td>90.0±1.1</td>
<td>89.8±1.2</td>
<td>.874</td>
</tr>
<tr>
<td>(89.0 to 92.2)</td>
<td>(88.2 to 91.5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Femoral component sagittal</td>
<td>3.1±1.7</td>
<td>4.6±2.2</td>
<td>.233</td>
</tr>
<tr>
<td>(1.8 to 4.7)</td>
<td>(2.2 to 6.1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tibial component sagittal</td>
<td>7.8±2.1</td>
<td>5.5±3.6</td>
<td>.010</td>
</tr>
<tr>
<td>(4.0 to 9.2)</td>
<td>(2.7 to 9.9)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Between femoral rotational axis and transepicondylar axis</td>
<td>0.7±0.3</td>
<td>3.6±2.2</td>
<td>.027</td>
</tr>
<tr>
<td>(0.3 to 1.2)</td>
<td>(0.9 to 5.9)</td>
<td></td>
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</tr>
</tbody>
</table>

Abbreviation: deg, degrees; MIS, minimally invasive; TKA, total knee arthroplasty.
daveric study, the number of samples available was small, and this small sample size may not provide sufficient statistical power to analyze all variables. In addition, clinical follow-up outcomes, such as knee scores, could not be investigated. Second, all cadavers did not show the same degree of arthritic change, including osteophytes, bony deformity, and soft tissue contracture, which may cause bias in the results between the 2 techniques. Third, only the accuracy of bone cutting was evaluated with robot-assisted minimally invasive TKA when other aspects should have been analyzed because TKA can achieve success not only in terms of accurate alignment but also in terms of well-balanced soft tissue.

In robot-assisted minimally invasive TKA, intraoperative tracking of ligament balance is lacking. However, Song et al. reported that well-balanced gaps and routine medial soft tissue release were achieved in more than 90% of cruciate-retaining TKAs after the robotic milling process. These results are comparable with those reported by Griffin et al., in which 3 mm of flexion-extension mismatch was noted in 13.5% of TKAs laterally and 10.6% of TKAs medially. These satisfactory results may be due to accurate femoral component rotation and the restoration of a normal tibial slope based on preoperative CT data.

**CONCLUSION**

Robot-assisted minimally invasive TKA showed excellent precision in the sagittal and coronal planes of 3-D CT scans. Higher implantation accuracy in femoral rotational alignment and tibial sagittal alignment and fewer outliers in various radiographic parameters were achieved with the modified instruments and tissue-sparing tunneling method. Minimally invasive TKA in combination with an improved robot-assisted technique is an alternative option to compensate for the shortcomings of conventional minimally invasive TKA.

**REFERENCES**