Canine angular limb deformities may result from various causes, including hereditary factors, premature closure of physes, and malunions. Particularly, pelvic limb deformities are occasionally accompanied by cranial cruciate ligament (CrCL) injuries and medial patellar luxation (MPL). Dogs having CrCL injuries or MPL with concurrent pelvic limb deformities are difficult to treat with common surgeries. Tibial plateau leveling osteotomy (TPLO) alone is unsuitable for dogs with excessive tibial plateau angle (TPA) and cannot correct concurrent tibial deformities. The classical treatments for MPL, such as tibial tuberosity transposition (TTT) and trochlear block recession (TBR), may be insufficient for dogs with excessive pelvic limb deformities in terms of postoperative risk of patellar relaxation. Therefore, if pelvic limb deformities are considered clinically significant in patients with CrCL injury or MPL, a corrective osteotomy is recommended.

Corrective osteotomies are technically difficult, particularly in chondrodystrophic or small breeds, and accuracy is important to optimize surgical outcomes. In preoperative planning, the...
assessment is more challenging in biapical deformities than in uniaxial deformities, and the presence of torsion interferes with the accurate measurement of deformities. A CT examination allows 3-D images of limbs contributing to the successful planning of the surgical correction. However, translating the planned correction from virtual images to patients remains a challenge. Thus, patient-specific 3-D–printed guides have been utilized for corrective osteotomy in dogs, facilitating accurate and simplified correction.

As antebrachial deformity is the most common angular limb deformity in dogs, most of the guided corrections have been performed for antebrachial deformities in dogs. Unlike the compressed morphology of the radius, the proximal tibia is triangular in cross section. This tibial morphology could make aligning the saw blade orthogonal to the long axis and initiating the osteotomy challenging. The difficulty may be compounded for tibias with deformities. While 1 study utilized patient-specific guides to perform several corrective osteotomies for angular limb deformities including tibia, there were no reports describing the process and clinical outcomes of tibial corrective osteotomies using patient-specific guides.

This study aimed to describe the design and application of patient-specific 3-D–printed osteotomy, reduction, and compression guides for tibial closing wedge osteotomy in dogs with various degrees of tibial deformities, including excessive TPA, valgus, and torsion. We evaluated the accuracy of the guides by comparing the postoperative angle with the planned angle and assessed the clinical outcomes in 6 dogs.

Methods

Inclusion criteria and data collection

Dogs that underwent unilateral tibial deformity correction using patient-specific 3-D–printed guides at Seoul National University, Seoul, Korea, and Ilsan Animal Medical Center, Goyang-si, Korea, between February 2020 and February 2023 and had at least a 6-month follow-up were included in this study. Data from the medical records (using the terms “tibial corrective osteotomy,” “patient-specific,” and “3-D–printed guide”), including signalment, breed, age, body weight, history, physical and orthopedic examination findings, preoperative imaging results, type of tibial deformity, surgical procedure, and postoperative follow-up assessment, were obtained. Client consent to perform the procedure and utilize medical records was obtained in all dogs. Subjective lameness grading was recorded according to 5 lameness criteria by the clinician referring to clients’ assessments and gait analysis data in available cases (none, 0; subtle weight-bearing lameness, 1; evident weight-bearing lameness, 2; intermittent non-weight-bearing lameness, 3; and consistent non-weight-bearing lameness, 4). A CT examination allows 3-D images of limbs contributing to the successful planning of the surgical correction. However, translating the planned correction from virtual images to patients remains a challenge. Thus, patient-specific 3-D–printed guides have been utilized for corrective osteotomy in dogs, facilitating accurate and simplified correction.

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Patient-specific guide design

Orthogonal radiographic and CT images (Aquilion 64; Toshiba Medical Systems) of bilateral pelvic limbs were obtained. Digital Imaging and Communication in Medicine images were transferred to image analysis software (3D Slicer; National Alliance for Medical Image Computing) to create a stereolithography file of relevant osseous structure. The threshold for segmentation of osseous structure was set at 200 Hounsfield units to optimize the contact surface of the guide considering the soft tissue between the guide and the bone. The resulting stereolithography files were exported to computer-aided design software (3DS Max; Autodesk) to simulate a virtual tibial closing wedge osteotomy and create patient-specific guides. Tibial deformities were characterized by identifying the location of the center of rotation of angulation (CORA) and measuring the joint angles according to a previous report based on CT data (Figure 1). The mechanical angles of the tibia, anatomical angles of the femur, and overall alignment of the affected limb were assessed. Tibial deformities were categorized as excessive TPA, valgus, and torsion, and all dogs exhibited 1 or a combination of these. None of the femurs required a surgical correction. The virtual wedge was created using transverse planes at the CORA level. The distal segment was manipulated to close the wedge until the target joint angle was achieved with a normal tibial alignment. Although the target TPA was set to not exceed 6°, the angle was set higher in excessive TPA cases, defined as a TPA > 34°, but did not exceed 14°. The target mechanical medio-proximal tibial angle (mMPTA) was referred to as the unaffected opposite limb or normal range of the published report. In the case of concurrent tibial torsion, the distal segment was planned to rotate at the osteotomy line to the angle at which the stifle and tarsal joints achieved the same longitudinal alignment. The normal range of tibial torsion angle (TTA) was also determined. Tibias with proximal valgus and excessive TPA or CrCL injuries were planned to be corrected with both TPA and mMPTA simultaneously with a single wedge. This was attributed to the fact that these deformities were planar and shared the CORA location on the proximal tibia in the oblique plane. To minimize limb shortening while reducing TPA, a modified cranial closing wedge osteotomy (CCWO) technique was planned, in which the proximal osteotomy line intersects the distal line. The contact surface of the osteotomy guide was an inverted representation of a specific anatomical contour of the proximal tibia conforming to the topography from the cranial to medial aspect, especially including the prominent structure of the tibial crest. The osteotomy guide contained saw-supporting shelves in the same plane as the osteotomy lines. Four to 5 thin, breakable bridges connected the proximal and distal shelves. The osteotomy guide incorporated cylindrical sleeves with a clearance of 0.05 mm for the insertion of 4 actual fixation K-wires (1.0 to 1.25 mm) and 2 temporary fixation K-wires (0.8 to 1.0 mm) to supply additional stability. The trajectories of the 4 actual fixation K-wires, in which 2 each were at the proximal and distal sites to the wedge, were positioned according to the degree of angle correction. The K-wires
were aligned in parallel after reduction. The reduction guide was anatomically contoured to the repositioned tibial surface. A compression guide, created to fit on the top of the reduction guide, was placed over the reduction guide. Both guides had 4 holes to align the K-wires (Figure 1). This guide module had oblique installation pins, in which the central axes of holes in a reduction guide and the central axes of holes in a compression guide were not coincident in a situation where the diameter of the guide hole was slightly larger with a clearance of 0.05 mm than that of the pin. The 2 proximal holes of the compression guide were positioned at the upper side based on the alignment site, forming oblique lines inclined in the direction from the upper side to the lower side. The 2 distal holes of the compression guide were positioned at the lower side based on the alignment site, forming oblique lines inclined in the direction from the lower side to the upper side. Consequently, the alignment site of the bone would be compressed.

The osteotomy, reduction, and compression guides were 3-D printed (Pixel One; Zerone) using a biocompatible urethane acrylate resin (SG-Clear; Dentis) as the material. After printing, the guides were washed a total of 3 times with 99% ethanol, with the last washing being ultrasonic cleaning, and cured with UV light (LC-3DPrint Box; 3D Systems). Tibial bone models based on CT data were 3-D printed (Shuffle XL; Phrozen) with resin (Harpiks; Zerone) for preoperative rehearsal to evaluate the adequacy of tibial alignment and whether the deformities were corrected appropriately (Figure 2). During rehearsal surgery, a bone plate was selected and precontoured to fit the postcorrected bone model. The printed guides and bone models were plasma sterilized before surgery.

**Surgical technique**

Cefazolin (33 mg/kg, IV) was administered for the preoperative antibiotic prophylaxis and repeated every 120 minutes. The dogs were premedicated with remifentanil (1 μg/kg, IV), ketamine (0.5 mg/kg, IV), and meloxicam (0.2 mg/kg, IV) for the preemptive analgesia. Anesthesia was induced with alfaxalone (2 mg/kg, IV) or propofol (6 mg/kg, IV) and maintained with an isoflurane-oxygen mixture. The constant rate infusion of remifentanil (0.01 mg/kg/h), midazolam (0.02 mg/kg/h), and ketamine (0.3 mg/kg/h) combination was administered perioperatively. The affected limbs were aseptically prepared by clipping and scrubbing. The dogs were positioned in dorsal recumbency, and the limbs were draped using the 4-quarter method.

After incising the medial proximal tibia, the cranial tibialis muscle and fascia were elevated using periosteal elevators. The osteotomy guide was placed in a specific position without mobility when applied and secured using temporary and actual fixation K-wires (Figure 3). Wedge osteotomy was performed using an oscillating saw supported by guide
shelves. After breaking the connecting bridges of the guide, the temporary fixation K-wires and osteotomy guides were removed, leaving the 4 fixed K-wires in place. The proximal and distal bone segments were repositioned after the insertion of the K-wires into the reduction and compression guides.

The osteotomy was stabilized using a preselected and contoured plate.

Dogs with MPL (cases 5 and 6) also underwent trochlear block recession and soft tissue reconstruction (medial release, lateral imbrication), and additional TTT or lateral fabello-tibial suture was

Figure 2—The rehearsal surgery using 3-D–printed tibial model and patient-specific guides in case 4. A—After the osteotomy guide was positioned in a specific location, temporary and actual fixation K-wires were inserted through the sleeves of the osteotomy guide. B—The wedge bone block was removed after osteotomy. C—After removal of the bridges, temporary pins, and osteotomy guides, actual fixation K-wires were inserted into the reduction and compression guides. The most proximal K-wire was parallel to the rest K-wires in the reduction guide, while after applying the compression guide, it was slightly bent proximally, which was the intended oblique direction for interfragmentary compression. The correction of valgus and torsion and reducing tibial plateau angle were performed simultaneously. The mosquito hemostatic forceps were used to prevent the dislocation of the compression guide.

Figure 3—Intraoperative images of a tibial biplanar and torsion correction in case 4. A—The osteotomy guide is secured with two 0.8-mm and four 1.0-mm K-wires. B—After completion of the osteotomy, thin guide bridges and temporary fixation K-wires are removed. C—The tibial deformities are corrected by aligning the K-wires with the reduction and compression guides. The most proximal K-wire was slightly bent proximally, as in the rehearsal surgery. D—The osteotomy is stabilized by a 1.5/2.0-mm tibial plateau leveling osteotomy plate.
performed according to the surgeon’s judgment to provide ancillary assistance for limb alignment. In case 2, tibial cranial thrust occurred when the tibia was internally rotated; thus, lateral fabello-tibial suture was additionally performed. In case 3, the tibial tuberosity avulsion fracture was stabilized by tension band wiring after closing wedge osteotomy. Postoperative radiographic or CT images were obtained to compare the postoperative angles with the target angles (Figure 4). If the evaluation of TTA was limited to patients without a postoperative CT scan (cases 4 and 5), orthogonal radiographs were obtained to evaluate whether the stifles and tarsal joints achieved the same longitudinal alignment.

Follow-up

Follow-up orthopedic examinations and radiographic evaluations were scheduled at 1, 2, 4, and 6 months after the surgery. Additional follow-up data were recorded when available. Subjective lameness grading and radiographic evaluation of the osseous union were recorded at each postoperative assessment. All complications were recorded during the follow-up. The mean and SD of the body weight, age, preoperative lameness score, amount of correction error, follow-up time, period to achieve a normal level of gait, and radiographic osseous union after surgery were calculated.

Results

Six dogs underwent unilateral tibial closing wedge osteotomy using patient-specific 3-D–printed guides (Table 1). These dogs had the following breeds: Bichon Frise (n = 1), Welsh Corgi (1), Poodle (1), Maltese (1), Chihuahua (1), and Pomeranian (1). The mean body weight was 5.7 ± 3.3 kg (range, 3.1 to 11.0 kg). The mean age was 4.2 ± 3.4 years (range, 1 to 10 years). Four dogs were castrated males, and 2 were spayed females. The preoperative lameness score was 2.3 ± 1.0, indicating evident lameness. Corrections for valgus alone (n = 1), TPA alone (1), TPA and torsion (2), and TPA reduction with correction for valgus and torsion (2) were planned. Concurrent stifle joint problems included medial patellar luxation (n = 2), CrCl injury (2), and tibial tuberosity avulsion fracture (1).

All osteotomy and reduction guides were successfully positioned at the planned locations. As the osteotomy guides fitted correctly and sterilized bone models aided in visual assessment, there was no intraoperative radiation exposure resulting from imaging assessments, such as fluoroscopy and radiography. The osteotomy was also successfully performed in direct contact with the shelves of the guide in all dogs, and an observer to assist with the saw blade orientation was not required.

The target postoperative angles, actual postoperative angles, and the differences between them were assessed (Table 2). In the 5 dogs in which reducing TPA was planned, the mean difference between target and postoperative TPA was 1.8 ± 1.4°. In the 3 dogs in which valgus correction was planned, the mean difference between target and postoperative mMPTA was 2.3 ± 2.1°. Two of the 4 dogs with torsional correction (cases 4 and 5) did not have postoperative CT images; therefore, postoperative TTA measurements were replaced with postoperative orthogonal radiographs. The postoperative radiography revealed that the stifles and tarsal joints were similarly oriented. In the 2 dogs in which torsion correction was planned, the mean difference between target and postoperative mMPTA was 2.3 ± 2.1°. Two of the 4 dogs with torsional correction (cases 4 and 5) did not have postoperative CT images; therefore, postoperative TTA measurements were replaced with postoperative orthogonal radiographs. The postoperative radiography revealed that the stifles and tarsal joints were similarly oriented. In the 2 dogs in which torsion correction was planned, the mean difference between target and postoperative TTA was 2.6 ± 1.3°. The minimal difference was 0°, which was the correction of the mMPTA in case 4, and the maximal difference was 4°, which was the correction of the mMPTA in case 6 and TPA in case 4.

All plate sizes were prepared and precontoured according to the postcorrected tibial models. TPLO plates were used in dogs that underwent CCWO and in case 4. The 1.5/2.0-mm ARIX VET TPLO plates (ARIX VET; Jeil Medical Co) were placed on the medial aspect of the tibia of dogs weighing < 5 kg.

Figure 4—Pre- and postoperative radiographs of case 4 (A and B) following tibial biplanar and torsion correction and CT of case 3 (C and D) following correction of excessive tibial plateau angle (TPA) and torsion. A—Reduced TPA was identified in mediolateral views. There were cancellous autografts gained from the removed wedge. B—Correction of proximal tibial valgus and torsion was identified in craniocaudal views. C—Excessive TPA was reduced and the tibial tuberosity avulsion fracture was stabilized with tension band wiring. D—Torsion correction was identified through the proximal and distal tibia achieving the same longitudinal alignment. The osteotomies were stabilized with 1.5/2.0-mm tibial plateau leveling osteotomy plates in both cases.
Table 1—Clinical summaries of cases that underwent tibial corrective osteotomy with 3-D–printed custom guides

<table>
<thead>
<tr>
<th>No.</th>
<th>Breed</th>
<th>Age (y)</th>
<th>Sex</th>
<th>Body weight (kg)</th>
<th>Tibial deformity</th>
<th>Other problems</th>
<th>Procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bichon Frise</td>
<td>6</td>
<td>MC</td>
<td>8.7</td>
<td>eTPA</td>
<td>CrCL rupture</td>
<td>mCCWO</td>
</tr>
<tr>
<td>2</td>
<td>Welsh Corgis</td>
<td>10</td>
<td>FS</td>
<td>11</td>
<td>Torsion</td>
<td>TT avulsion fracture</td>
<td>mCCWO, LFTS</td>
</tr>
<tr>
<td>3</td>
<td>Poodles</td>
<td>1</td>
<td>MC</td>
<td>4.3</td>
<td>eTPA, torsion</td>
<td>CrCL partial rupture</td>
<td>mCCWO, TBW</td>
</tr>
<tr>
<td>4</td>
<td>Maltese</td>
<td>3</td>
<td>FS</td>
<td>3.3</td>
<td>Valgus, torsion</td>
<td>Biplanar wedge osteotomy</td>
<td>MCL4</td>
</tr>
<tr>
<td>5</td>
<td>Pomeranian</td>
<td>1</td>
<td>MC</td>
<td>3.1</td>
<td>Valgus, eTPA, torsion</td>
<td>Biplanar wedge osteotomy, MPLR</td>
<td>MCWO, MPLR</td>
</tr>
<tr>
<td>6</td>
<td>Chihuahua</td>
<td>4</td>
<td>MC</td>
<td>3.9</td>
<td>Valgus</td>
<td>MCL4</td>
<td></td>
</tr>
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</table>

CrCL = Cranial cruciate ligament. eTPA = Excessive tibial plateau angle. FS = Female spayed. LFTS = Lateral fabello-tibial suture. MC = Male castrated. mCCWO = Modified cranial closing wedge osteotomy. MCL4 = Medial closing wedge osteotomy. MPL = Medial patellar luxation. MPLR = Medial patellar luxation repair. TBW = Tension band wiring. TT = Tibial tuberosity.

Table 2—Pre- and postoperative and target tibial angles: difference between the target and achieved angles.

<table>
<thead>
<tr>
<th>No.</th>
<th>TPA (°)</th>
<th>Pre-OP</th>
<th>Post-OP</th>
<th>Difference</th>
<th>mMPTA (°)</th>
<th>Pre-OP</th>
<th>Post-OP</th>
<th>Difference</th>
<th>TTA (°)</th>
<th>Pre-OP</th>
<th>Post-OP</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>64.0</td>
<td>7.0</td>
<td>8.7</td>
<td>1.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-22.2</td>
<td>6.7</td>
<td>3.2</td>
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</tr>
<tr>
<td>2</td>
<td>20.5</td>
<td>5.7</td>
<td>6.7</td>
<td>1.0</td>
<td>-22.2</td>
<td></td>
<td></td>
<td></td>
<td>-22.2</td>
<td>6.7</td>
<td>3.2</td>
<td>3.5</td>
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<tr>
<td>3</td>
<td>50.8</td>
<td>11.1</td>
<td>8.9</td>
<td>2.2</td>
<td>31.3</td>
<td></td>
<td></td>
<td></td>
<td>94.0</td>
<td>14.7</td>
<td>13.1</td>
<td>1.6</td>
</tr>
<tr>
<td>4</td>
<td>25.0</td>
<td>6.0</td>
<td>10.0</td>
<td>4.0</td>
<td>94.0</td>
<td></td>
<td></td>
<td></td>
<td>94.0</td>
<td>14.7</td>
<td>13.1</td>
<td>1.6</td>
</tr>
<tr>
<td>5</td>
<td>34.0</td>
<td>21.0</td>
<td>20.8</td>
<td>0.2</td>
<td>94.0</td>
<td></td>
<td></td>
<td></td>
<td>95.0</td>
<td>14.7</td>
<td>13.1</td>
<td>1.6</td>
</tr>
<tr>
<td>6</td>
<td>14.0</td>
<td>8.7</td>
<td>8.7</td>
<td>1.7</td>
<td>97.0</td>
<td></td>
<td></td>
<td></td>
<td>101.0</td>
<td>14.7</td>
<td>13.1</td>
<td>1.6</td>
</tr>
</tbody>
</table>

mMPTA = Mechanical medio-proximal tibial angle. Post-OP = Postoperative angle. Pre-OP = Preoperative angle. TPA = Tibial plateau angle. TTA = Tibial torsion angle.

The 2.4-mm TPLO plates, including the Synthes (DePuy Synthes; Johnson & Johnson MedTech) and ARIX Vet TPLO plates, were used for dogs weighing > 5 kg. The 2.0-mm straight plates were used in cases 5 and 6 (Synthes LCP 9 holes for case 5 and ARIX Vet straight plate 7 holes for case 6).

Clinical reevaluation and radiographic follow-up were performed in all dogs. Five dogs recovered to the normal gait at a mean of 14.8 ± 6.6 weeks postoperatively. Case 3 recovered to subtle weight-bearing lameness 24 weeks after surgery. In the radiographic follow-up, all limbs healed to good osseous union at a mean of 14.0 ± 4.7 weeks postoperatively. The mean follow-up time was 36.8 ± 17.0 weeks. No intraoperative or postoperative complications required revision surgery. The skin infections in cases 2 and 3 resolved with antibiotics within 1 month. Skin irritation was self-limiting in case 1.

Discussion

This study described the design and clinical use of patient-specific 3-D–printed osteotomy, reduction, and compression guides to correct tibial deformities by closing wedge osteotomy. The use of patient-specific guides allowed sufficient correction of tibial valgus, torsion, and excessive TPA with minimal error. For the stable contact of the osteotomy guide on the bone, the guide-bone interface region typically includes the unique osseous topography such as the extensor groove and distal physeal scar of the distal radius.46,38 Even though we did not incorporate the caudal aspect of the tibia to reduce the soft tissue damage, unlike a previous report39 of the tibial patient-specific pin guides, the protruding tibial crest allowed the osteotomy guide to be accurately positioned. All 6 limbs were corrected to normal alignment with good radiographic union. Only mild complications that resolved within 1 month were observed, and no revision surgery was required. Patient-specific 3-D–printed guides could provide effective surgical assistance allowing accurate corrective osteotomy for tibial deformities in dogs.

In the correction of 10 tibial angles in 6 dogs, the angular errors were 1.8 ± 1.4°, 2.3 ± 2.1°, and 2.6 ± 1.3° in the sagittal, frontal, and transverse planes, respectively. These differences might originate from guide fabrication, errors in guide application due to adherent soft tissue, and osseous displacement during fixation.26,28 Hall et al26 defined the range of acceptable difference as within ± 2°, and Carwardine et al27 reported average angular differences of 3.5° in the frontal plane and 7.5° in the sagittal plane. More recent studies using 3-D–printed guides by De Armond et al26 and Townsend et al38 defined an acceptable difference of up to 5°. Our achieved angle differences were within 5° and comparable to the stricter criteria of 2°. In an in vitro study28 describing the accuracy of corrective osteotomy of canine tibial replicas using a customized osteotomy guide and plate, the angular error of TPA was 0.6 ± 0.4°. As our results were derived from clinical cases with soft tissue that could affect guide position and limit visualization,28 the angular error was considered acceptable even though it was larger than the corresponding in vitro results. Thus, patient-specific 3-D–printed guides seem to be effective surgical equipment to correct tibial deformities accurately, as well as previously reported antebrachial and femoral deformities in dogs.
Modified CCWO, in which the proximal osteotomy line intersects the distal line, is a balanced option for correcting excessive TPA in terms of minimal mechanical changes and sufficient osteotomy apposition.\textsuperscript{16,36} Modified CCWO also results in positive clinical outcomes; however, the challenge of osteotomies with intersecting angles results in some inaccuracies, even with the aiming device in the previous study.\textsuperscript{37} Postoperative TPA is particularly high in small-breed dogs weighing < 20 kg owing to the small wedge size resulting in a loss of planning accuracy and technical difficulty.\textsuperscript{37} We achieved the accurate osteotomy with good clinical outcomes, despite the fact that all dogs that underwent the modified CCWO in this study were small breeds weighing approximately 5.7 kg. Therefore, when performing a modified CCWO, which requires a more delicate osteotomy than a conventional CCWO on small bones, 3-D-printed guides can aid in obtaining an accurate osteotomy even in small-breed dogs.

Antebrachial deformity is the most common angular limb deformity and loss of coordinated growth between the radius and ulna leads to multiplanar deformities in dogs.\textsuperscript{26,29} Although these complex deformities complicate surgical correction, they have been successfully corrected using patientspecific guides.\textsuperscript{26,27,29,30} Unlike the radius, which has a compressed shape, the morphology of the proximal tibia is triangular in cross section, which could make initiating and aligning orthogonal osteotomy difficult.\textsuperscript{32} Additionally, performing orthogonal tibial osteotomies can be particularly challenging in dogs with small bone sizes, chondrodystrophic limbs, and highly divergent osteotomy angles owing to the variation in cortical margin contour for proximal and distal osteotomies.\textsuperscript{18} In this study, case 2 had a chondrodystrophic tibia with external torsion of the proximal tibia and minor distal deformities, such as distal varus and recurvatum. Case 3 had highly divergent angles and an irregular proximal tibial cortex resulting from the healing of osteomyelitis in the immature period. Case 4 was planned to correct the combination of 3 angular deformities and had a history of previous TTT surgery, which resulted in lateral deviation of the tibial tuberosity. Despite these abnormal factors, we performed orthogonal corrective osteotomy with a single wedge using patient-specific guides that could be customized to any bone shape. Therefore, dogs with an abnormal tibial morphology or high correction angles may be suitable candidates for corrective osteotomy using patient-specific guides.

Angular limb deformities are often complex, such as multiplanar deformities, and quantifying the angles for surgical planning is difficult.\textsuperscript{26,27} The biplanar deformity, which is a combination of frontal and sagittal plane angulations, is actually a uniplanar deformity in the oblique plane. Evaluating the oblique plane using radiographs requires additional procedures, such as vector calculation between the CORA angles in orthogonal radiographic views.\textsuperscript{41} Recently, the 3-D reconstruction of the affected limb using CT data has been used for the visual configuration of the CORA location and wedge direction. This allows easier planning and correction of multiplanar deformities.\textsuperscript{26,27,29,30} We used 3-D-reconstructed bone models to identify the oblique plane for a biplanar deformity and reduced TPA and mMPTA simultaneously by a single closing wedge osteotomy. Torsion correction was simultaneously achieved by rotating the distal segment of the osteotomy line. Three-dimensional virtual modeling using CT can simplify the visual configuration of the deformity even when the deformity is complex and consequently allow the creation of patient-specific osteotomy guides that can allow the surgery to be performed as planned.

We utilized the compression guide to achieve interfragmentary compression, as the reduction guide primarily focused on apposition. Theoretically, the proximal and distal pins each formed oblique lines inclined toward the osteotomy site, and as shown (Figures 2 and 3), the intended oblique direction occurred during rehearsal and clinical surgery. Since there has been no published quantitative evaluation of the interfragmentary compression, additional laboratory tests may support the benefit of the oblique installation pin module. As this study focused on the process for clinical application rather than specific manufacturing processes, the specific accuracy of the guides was not measured. Further studies could strengthen the reliability of the 3-D-printed guides by measuring the relative importance of sources of inaccuracies, such as guide design, fabrication, sterilization, and placement. Owing to the small number of dogs and the retrospective nature of this study, a comparison of our results with those of the conventional method was not possible. Further prospective evaluations with larger sample sizes should demonstrate their usefulness when comparing the use of these guides with traditional approaches to tibial deformity correction. For this method, additional costs and time are involved in CT scanning and guide production compared with conventional techniques. However, corrective osteotomy using these guides is considered sufficient to endure additional cost and time, especially for dogs with tibias with abnormal geometry.

In conclusion, patient-specific 3-D-printed osteotomy, reduction, and compression guides for tibial closing wedge osteotomy allow for simplified accurate correction of tibial deformities, even in dogs with challenging factors, such as small or irregular bones and requiring multiple angle correction. This guide design and surgical procedure can serve as a reference, and further prospective studies with a larger number of patients can establish the guides’ effectiveness over conventional techniques.

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**Disclosures**

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