Efficacy of two reduction methods in conjunction with 3-D–printed patient-specific pin guides for aligning simulated comminuted tibial fractures in cadaveric dogs

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OBJECTIVE
To assess the feasibility and accuracy of using 2 methods for reduction and alignment of simulated comminuted diaphyseal tibial fractures in conjunction with 3-D–printed patient-specific pin guides.

SAMPLE
Paired pelvic limbs from 8 skeletally mature dogs weighing 20 to 35 kg.

METHODS
CT images of both tibiae were obtained, and 3-D reconstructions of the tibiae were used to create proximal and distal patient-specific pin guides. These guides were printed and used to facilitate fracture reduction and alignment in conjunction with either a 3-D–printed reduction guide or a linear type 1A external fixator. Postreduction CT images were used to assess the accuracy of pin guide placement and the accuracy of fracture reduction and alignment.

RESULTS
The 3-D–printed guides were applied with acceptable ease. Guides for both groups were placed with minor but detectable deviations from the planned location (P = .01), but deviations were not significantly different between groups. Fracture reduction resulted in similar minor but detectable morphological differences from the intact tibiae (P = .01). In both groups, fracture reduction and alignment were within clinically acceptable parameters for fracture stabilization by means of minimally invasive plate osteosynthesis.

CLINICAL RELEVANCE
Virtual surgical planning and fabrication of patient-specific 3-D–printed pin guides have the potential to facilitate fracture reduction and alignment during use of minimally invasive plate osteosynthesis for fracture stabilization.

Minimally invasive plate osteosynthesis (MIPO) is an emerging treatment modality in small animal orthopedics.1–5 MIPO uses indirect reduction techniques to align the major fracture segments prior to implant application. Manual traction, intramedullary pins, external fixators (EFs), and appropriate plate contouring have been used to facilitate indirect closed reduction of appendicular long bone fractures during MIPO in dogs.1,2,6–14 Gaining proficiency in MIPO can be technically challenging, and the availability of intraoperative fluoroscopy greatly facilitates the process.15,16–17

Virtual surgical planning based on CT imaging and 3-D printing are being used with increasing frequency in both human and small animal orthopedic surgery.18–32 Virtual modeling affords creative preoperative formulation of surgical procedures and allows for the fabrication of bone models and patient-specific guides that can be used prior to or during surgery.33 Guides are designed to conform to specific topographic features on a bone’s surface, enabling a precise, congruent fit between the guide and bone. Fabricated patient-specific guides have been used as drill, osteotomy, and reduction guides (RGs) to facilitate and maintain alignment for implant placement.23,27,30,34–37 A recent cadaveric study27 evaluated the potential use of virtual surgical planning with application of a printed alignment jig for managing fractures in dogs. In that study, Lynch and Davies27 used a cadaveric tibial fracture model and developed a 2-stage surgical process that included placing pins in the major proximal and distal tibial fracture segments during an initial surgical procedure. The fractured limbs, with implanted pins, were then imaged
with CT, and the CT volume data were subsequently used to virtually reduce and align the fractured tibia. A reduction jig was developed to articulate the pins securing the proximal and distal fracture segments during a virtual surgical planning session. The jig was then fabricated and applied during a second surgical procedure to reduce and align the fractured tibia.27

For the present study, we proposed that custom pin guides fabricated with virtual 3-D renderings of CT images of intact tibiae could be applied to accurately reduce a simulated comminuted, mid diaphyseal tibial fracture. We were specifically interested in assessing the efficacy of 2 methods of articulating the attached pin guides to reduce and align the fractured tibiae and postulated that both methods would yield acceptable fracture alignment. This methodology could be used in clinical cases, because guides could be designed on the basis of a mirror image of the contralateral, intact tibia, requiring only a single CT and surgical procedure.

The objective of the study reported here was to assess the utility and reliability of designing, printing, and applying 3-D–printed patient-specific pin guides to facilitate reduction and alignment of tibiae with simulated comminuted, mid diaphyseal fractures. We evaluated 2 reduction systems with regard to speed and simplicity of application as well as accuracy of fracture reduction, including the restoration of prefracture tibial length and torsional, frontal, sagittal plane alignment.

We hypothesized that use of patient-specific pin guides, regardless of reduction technique, would restore acceptable anatomic length (discrepancy of ≤5 mm, compared with length of the intact tibia) and facilitate acceptable fracture reduction (translation of ≤3 mm) and frontal, sagittal, and torsional alignment (deviations of ≤5°, ≤10°, and ≤5°, respectively, compared with the intact tibia).7,14,38,39

We further hypothesized that use of a 3-D–printed RG would result in shorter reduction times with less difficulty and would yield more accurate reduction and alignment, compared with manual reduction with a linear EF.

**Materials and Methods**

Cadavers of 8 skeletally mature dogs weighing 20 to 35 kg that had been euthanized for reasons unrelated to the present study were acquired. The dogs’ tibiae were palpated to screen for normalcy, and cadavers were included if no palpable abnormalities were noted. Cadavers were frozen at −30°C until imaging could be performed. Cadavers were thawed prior to CT (Aquilion Prime S computed tomography scanner; Canon Medical Systems) of both pelvic limbs. Helical volume data (slice thickness of 0.5 mm and 0.3-mm slice overlap) were acquired. The bone algorithm was used for all 3-D reconstructions and analyses.

DICOM files of the CT images of the tibiae were imported into a proprietary software program (Mimics; Materialise Medical Imaging Software Suite) for segmentation and 3-D modeling of anatomic structures, operative planning, and guide design. The length of each tibia, frontal, and sagittal angulation and degree of tibial torsion were measured according to methods previously described.40–42

The cadavers were stored in a −30°C C cooler until custom guides were designed and printed. Each dog’s right and left pelvic limbs were randomly assigned by coin toss to an RG and an EF group.

**Guide design**

All guides were developed on the basis of CT images of the intact tibiae. These 3-D–rendered models were assessed for digital imperfections, corrected, and subsequently exported to the proprietary software program. Data were then exported as stereolithography files to a proprietary software printing program (Insight; Stratasys) to generate toolpaths for printing of the models. Subsequently, the 3-D models were printed (Fortus 450mc; Stratasys) with a T12 tip (0.178-mm layer thickness) in a biocompatible acrylonitrile butadiene styrene material, with a final print accuracy of ±0.127 mm.

Rendered images of the intact tibiae served as the control for rendered images of the fractured tibiae following reduction.

The proximal pin guides were designed to conform to the topography of the cranial, medial, and caudal aspects of the proximal portion of the tibia. The basic pin guide design consisted of 3 components: pin sleeves, bridge, and patient-specific base (Figure 1). Each guide had 2 identical 10-mm cylindrical pin sleeves with a 30° divergence; the sleeve closest to the fracture was oriented perpendicular to the long axis of the tibia. Divergent pins afforded greater RG stability while potentially mitigating pin interference if a plate were to be applied in a clinical situation. The sleeves were designed to accommodate 3.2-mm-diameter partially threaded pins (Duraface; IMEX Veterinary Inc). The bridge component consisted of a 25 X 10 X 20-mm rectangular prism that incorporated the 2 pin sleeves and contacted the cranial aspect of the tibia. The base established contact with the medial and caudal aspects of the tibia by means of 2 overlapping components consisting of a 25 X 10 X 25-mm rectangular prism on the medial aspect with a 7-mm-radius sphere and a 20 X 15 X 7-mm rectangular prism to capture the caudal tibial contours. Additionally, a hole was placed in the caudal region of each pin guide base, transverse to the long axis, to accommodate a 1.6-mm Kirschner wire. Once the desired anatomic location was determined on the basis of local topography and the template had sufficient contour and contact with the desired location, the topography of the tibia was subtracted by means of Boolean subtraction and a clearance factor of 0.4 mm from the modular template to create a patient-specific fit for each specimen. The distal pin guides were designed in a similar manner, but without the caudal rectangular prism, to conform to the cranial, medial, and caudal surfaces in the region of the distal tibial metaphysis. All of the sleeves were designed to be aligned in the sagittal plane when applied to the tibia.
In the EF group, a type 1A linear EF consisting of 4 pin clamps and a carbon fiber connecting rod (SK system; IMEX Veterinary Inc) was applied to the pins to reduce and align the fractured tibia. The pin sleeve height was reduced for pin guides in the EF group so that the connecting rod of the EF would be positioned at a similar distance from the sagittal tibial mechanical axis as the 3-D printed RG. The remainder of the pin guide design was identical (mirror image) to the RG pin guide developed for that cadaver’s contralateral limb.

In the RG group, a 3-D–printed RG was designed to be applied to the pin sleeves to align and reduce the fracture. The printed RG consisted of a bivalved, 2-piece, 10-mm-high X 19-mm-wide rectangular block with sufficient length to accommodate all 4 pin sleeves. The RG was designed with 4 mirror-image, hemicylindrical recesses, created by means of Boolean subtraction, along the RG length at appropriate locations to secure the pin guide sleeves if the tibia was optimally aligned. The 2 component halves of the RG had 3 matching transverse holes to accommodate 4.8-mm bolts. Assembling the RG in contact with the pin sleeves was intended to restore anatomic alignment and length of the fractured tibiae. The RG was secured to the pin sleeves by placing wing nuts on the 3 bolts placed through the 2 component halves (Figure 1).

Guide application and fracture reduction

For both reduction groups, medial incisions were made over the proximal and distal aspects of the tibia to allow the 3-D patient-specific pin guides to be attached to the respective tibial segments at the specified locations. Once the pin guides were congruently placed on the tibia, a medial-to-lateral 1.6-mm Kirschner wire was placed to secure the guide to the tibia. A 3.2-mm partially threaded pin was then placed through each of the pin guide sleeves and seated in the caudal cortex of the tibia. Pin guides were attached to the intact tibia for ease of placement, with minimal assistance needed to hold the limb.

The time required to place the pin guides was recorded. Obtaining sufficient exposure for and ease of placement of the pin guides was subjectively assessed with a 10-point Likert-type scale: 0 = unable to achieve proper placement; 5 = guide placement with moderate soft tissue manipulation; and 10 = able to place guide easily with minimal extraneous soft tissue disruption (Supplementary Table S1).

Once the pin guides were secured, an incision was made over the medial aspect of the mid diaphysis of the tibia. Multiple osteotomies were made in a consistent pattern to create a simulated comminuted diaphyseal fracture. The fibula was fractured by angulating the crus through the osteotomy. The incision was closed in a single layer prior to any attempt at fracture reduction so that direct visual assessment of reduction was not possible.

For the RG group, the 3-D–printed RG was assembled, securing the pin guide sleeves. The bolts were placed through the holes in the RG, and wing nuts were applied to the bolts and tightened. For the EF group, pin clamps were loosely placed on each of the pins and a connecting rod was advanced, in a proximal-to-distal direction, through each of the clamps. Traction was applied to the pes to distract the fractured tibia to its original length, and the pins were manually aligned by rotating the pes as the clamps were tightened to stabilize the reduced tibia. The pin alignment was visually inspected. If the proximal and distal pins were not rotationally aligned, the clamps were loosened, and the reduction was improved prior to retightening the clamps (Supplementary Figure S1).

The time required for guide application and reduction was recorded. A subjective assessment of the efficiency and simplicity of this process was recorded on a 10-point Likert-type scale: 0 = unable to achieve acceptable reduction; 5 = fracture reduction achieved with marginally acceptable alignment;

Figure 1—3-D renderings of the right tibia of a dog with external fixator (EF) pin guides in their planned positions (A–D) and the left tibia of the same dog with reduction guide (RG) pin guides and the RG (gray) in place (E–H). Each tibia is shown in medial, cranial, lateral, and caudal views. For the cranial view of the left tibia (F), the RG has been removed to allow visualization of the pin guides.
and 10 = fracture reduction readily achieved with optimal alignment (Supplementary Table S1).

**Guide measurements**

CT imaging was performed following reduction of the tibiae. The DICOM images were processed in the same manner as described for the intact tibia. Metal suppression was used to reduce metallic artifact, with individual pin placement derived from the defect created by the pin in each tibia. Pin placement was then measured by virtually replacing the pin in each 3-D-rendered image to determine the accuracy of placement of the guides. Absolute values for distance or degree of deviation were derived by comparison against the intended virtual position for each pin. Actual placement measurements were given positive and negative values (medial vs lateral, cranial vs caudal, and proximal vs distal) that were averaged to determine the prevailing direction of pin deviation in a given plane. Pins were numbered 1 through 4 from proximal to distal. Intact tibiae and virtual patient-specific pin guides were overlapped with the proximal and distal segments of the postreduction tibiae. Point-to-point registration was used to accurately align the tibiae and move the guides without altering each guide’s planned location on each tibia. Actual pin placement was compared to the virtual planned location, and differences were recorded in each plane; angle deviations were also measured (Figure 2). All measurements were performed on the digital images.

**Postreduction imaging and fracture reduction measurements**

Tibial length, translation at the fracture site, frontal and sagittal plane angulation, and torsion were measured and compared with each specimen’s intact values. The frontal plane, proximal and distal joint orientation lines, and mechanical axis were defined with previously described points. Joint orientation lines and the mechanical axis were created with the use of datum planes oriented perpendicular to the frontal plane. The 2-D mechanical medial proximal tibial angle and mechanical medial distal tibial angle were measured (Figure 3).

Similarly, with tibiae viewed in the sagittal plane, points described by Dismukes et al. were used to create the proximal and distal joint orientation lines and mechanical axis as datum planes perpendicular to the sagittal plane. Intact and postreduction mechanical caudal proximal tibial angles and mechanical cranial distal tibial angles were measured (Figure 3).

To measure postreduction frontal and sagittal plane angulation, the mechanical axis defined on the intact tibia was transposed over the frontal and sagittal postreduction joint orientation lines. The mechanical axis was duplicated and oriented to cross the postreduction proximal and distal joint orientation lines at the angles measured on the
intact tibia. Frontal and sagittal angulation was then determined by measuring the angular difference between the 2 mechanical axes.

Overall reduction was graded as near anatomic (deviation of tibial length of ≤ 5 mm, translation of ≤ 3 mm, internal or external torsion and varus or valgus angulation of ≤ 5°, and procurvatum or recurvatum of ≤ 10°), acceptable (deviation of tibial length of ≤ 10 mm, translation of > 3 to ≤ 6 mm, internal or external torsion and varus or valgus angulation of ≤ 10°, and procurvatum or recurvatum of ≤ 20°), or unacceptable (deviation of tibial length of > 10 mm, translation of > 6 mm, internal or external torsion and varus or valgus angulation of > 10°, and procurvatum or recurvatum of > 20°).14,38,39

The absolute value of alterations in length, reduction, or alignment was used to assess the accuracy of reestablishing the intact tibial morphology for comparisons within and between reduction groups to negate the effects of bidirectional (eg, medial or lateral and cranial or caudal) variations between specimens.

Statistical analysis

Data were analyzed with the Wilcoxon signed rank test. A preliminary power analysis was performed to determine a minimum sample size for this comparison. Based on estimates of the precision of CT measurements, a minimum specimen number of 8 specimens was determined. The provided parameters were significance level (adjusted for sidedness) = 0.025, SD of the dependent variable = 4 mm, SD of the independent variable = 6 mm, number of tibiae = undefined, power = 0.9, and minimal detectable difference = 1. The variable calculated was the total number of tibiae. A total of 8 cadavers were used in this study. The probability was 93% that the study would detect a relationship between the independent and dependent variables at a 2-sided significance level of 0.05 if the true change in the dependent variables was 1.0-mm/mm change in the independent variable. This assumed that the SD of the independent variable was 6 and the standard deviation of the dependent variable was 4.

Results

Pin guide placement accuracy

Ease of placement of the proximal and distal pin guide was similar for the 2 reduction groups, with minor but measurable deviations from the planned location and orientation. Guide placement in all 3 planes showed small, significant (P = .01) deviations from the virtual location but was not significantly different between reduction groups in any plane (Table 1).

Ease of fracture reduction

Median scores for ease of fracture reduction were 10 (range, 9 to 10) and 8 (range, 7 to 10) for the RG and EF groups, respectively; these scores were significantly (P = .03) different. Median time to reduce the tibiae was 1.4 minutes (interquartile [25th to 75th percentile] range, 1.2 to 1.5 minutes) and 3.0 minutes (interquartile range, 2.3 to 4.4 minutes) for the RG and EF groups, respectively; these times were significantly (P = .02) different. In the EF group, fracture reduction had to be readjusted in 3 specimens owing to visible torsional malalignment following initial tightening of the EF clamps.

Fracture reduction accuracy

Fracture reduction accuracy was similar in the 2 reduction groups, with minor but measurable deviations from the intact tibiae (Tables 2 and 3). Fracture reduction in all 3 planes showed small, significant (P = .01 or .02) deviations from the intact tibiae,

Table 1—Accuracy of placement for 3-D–printed patient-specific pin guides fabricated from virtual 3-D renderings of CT images of intact tibiae from cadaveric dogs (n = 8 tibiae/group) and used to facilitate reduction and alignment (with a reduction guide [RG] or external fixator [EF]) of simulated comminuted diaphyseal tibial fractures.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Proximal pin guide</th>
<th>Distal pin guide</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RG group</td>
<td>EF group</td>
</tr>
<tr>
<td>Frontal plane deviation</td>
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<td></td>
</tr>
<tr>
<td>Median (IQR)</td>
<td>4.1° (2.1°–5.2°)</td>
<td>5.1° (2.8°–7.4°)</td>
</tr>
<tr>
<td>Prevailing direction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proximomedial</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P value⁵</td>
<td>&lt; 0.01</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>P value⁶</td>
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<td>NA</td>
</tr>
<tr>
<td>Transverse plane deviation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Median (IQR)</td>
<td>2.3° (1.4°–4.4°)</td>
<td>2.8° (1.2°–6.3°)</td>
</tr>
<tr>
<td>Prevailing direction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medial</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P value⁵</td>
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<td>0.01</td>
</tr>
<tr>
<td>P value⁶</td>
<td>0.4</td>
<td>NA</td>
</tr>
<tr>
<td>Sagittal plane deviation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Median (IQR)</td>
<td>1.1° (0.7°–3.4°)</td>
<td>2.6° (1.5°–3.8°)</td>
</tr>
<tr>
<td>Prevailing direction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proximal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P value⁵</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>P value⁶</td>
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<td>NA</td>
</tr>
<tr>
<td>Distomedial</td>
<td>3.2° (1.7°–5.8°)</td>
<td>3.2° (3.0°–4.0°)</td>
</tr>
<tr>
<td>P value⁵</td>
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<td>&lt; 0.02</td>
</tr>
<tr>
<td>P value⁶</td>
<td>0.6</td>
<td>NA</td>
</tr>
<tr>
<td>Distomedial</td>
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<td>6.6° (5.2°–8.2°)</td>
</tr>
<tr>
<td>P value⁵</td>
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<td>&lt; 0.001</td>
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<tr>
<td>P value⁶</td>
<td>0.8</td>
<td>NA</td>
</tr>
<tr>
<td>Proximomedial</td>
<td>1.4° (1.0°–2.6°)</td>
<td>3.4° (1.2°–4.4°)</td>
</tr>
<tr>
<td>P value⁵</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>P value⁶</td>
<td>0.06</td>
<td>NA</td>
</tr>
</tbody>
</table>

IQR = Interquartile (25th to 75th percentile) range. NA = Not applicable.
⁵P value for comparison with virtual location determined on the basis of CT images of intact tibiae.
⁶P value for comparison with deviation for the EF group.
Table 2—Accuracy of fracture reduction for tibiae from 8 cadaveric dogs when an RG or EF was used to facilitate reduction and alignment in conjunction with placement of 3-D–printed patient-specific pin guides fabricated from virtual 3-D renderings of CT images of the intact tibiae.

<table>
<thead>
<tr>
<th>Variable</th>
<th>RG group</th>
<th>EF group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change in tibial length (mm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Median (IQR)</td>
<td>0.8 (0.1–2.5)</td>
<td>2.3 (0.2–4.8)</td>
</tr>
<tr>
<td>Prevailing change</td>
<td>Increase</td>
<td>Decrease</td>
</tr>
<tr>
<td>$P$ value$^a$</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>$P$ value$^b$</td>
<td>0.3</td>
<td>NA</td>
</tr>
<tr>
<td>Mediolateral translation (mm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Median (IQR)</td>
<td>1.4 (0.7–2.6)</td>
<td>3.2 (2.6–4.3)</td>
</tr>
<tr>
<td>Prevailing change</td>
<td>Medial</td>
<td>Medial</td>
</tr>
<tr>
<td>$P$ value$^a$</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td>$P$ value$^b$</td>
<td>0.09</td>
<td>NA</td>
</tr>
<tr>
<td>Cranio-caudal translation (mm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Median (IQR)</td>
<td>0.8 (0.5–1.3)</td>
<td>2.1 (1.5–4.0)</td>
</tr>
<tr>
<td>Prevailing change</td>
<td>Cranial</td>
<td>Caudal</td>
</tr>
<tr>
<td>$P$ value$^a$</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>$P$ value$^b$</td>
<td>0.06</td>
<td>NA</td>
</tr>
</tbody>
</table>

IQR = Interquartile (25th to 75th percentile) range. NA = Not applicable.

$^aP$ value for comparison with intact tibiae.

$^bP$ value for comparison with deviation for the EF group.

but reduction was significantly different between reduction groups only in mediolateral translation ($P = .01$) and not in tibial length ($P = .3$) or mediolateral translation ($P = .09$).

All of the tibiae in the RG group had a ≤ 5-mm change in length, compared with length of the intact tibia. In the EF group, 7 tibiae had a ≤ 5-mm change in length and 1 had a > 5-mm change in length. In the RG group, 7 tibiae had an increase in length and 1 tibia had a length equal to that of the intact tibia. In the EF group, 5 tibiae had a decrease in length, 1 tibia had a length equal to that of the intact tibia, and 2 tibiae had an increase in length. The median change in tibial length was not significantly ($P = .3$) different between reduction groups.

The RG group had 7 tibiae that had ≤ 3 mm of mediolateral translation and 1 tibia with < 6 mm of mediolateral translation. In the EF group, 4 tibiae had ≤ 3 mm of mediolateral translation and 4 tibiae had < 6 mm of translation. The RG group had 6 tibiae with medial translation and 2 with lateral translation. The EF group had 5 tibiae with medial translation and 3 with lateral translation. Median absolute mediolateral translation was not significantly ($P = .09$) different between reduction groups.

All tibiae in the RG group had ≤ 3 mm of cranio-caudal translation. In the EF group, 5 tibiae had ≤ 3 mm of cranio-caudal translation, 2 tibiae had ≤ 6 mm of cranio-caudal translation, and 1 tibia had > 6 mm of cranio-caudal translation. In the RG group, 5 tibiae had caudal translation and 3 had cranial translation. In the EF group, 6 tibiae had caudal translation and 2 had cranial translation. Median absolute cranio-caudal translation was not significantly ($P = .01$) different between reduction groups.

In the RG group, the change in frontal plane angulation was ≤ 5° in 6 tibiae and ≤ 10° in 2 tibiae. In the EF group, the change in frontal plane angulation was ≤ 5° in 6 tibiae, ≤ 10° in 1 tibia, and > 10° in 1 tibia. Valgus deviation was present in 6 tibiae in both reduction groups, and varus deviation was present in 2. Median absolute change in frontal plane alignment was not significantly ($P = .6$) different between reduction groups.

Sagittal plane angulation was ≤ 10° in all tibiae in both reduction groups. In the RG group, 4 tibiae had recurvatum, and 4 tibiae had procurvatum. In the EF group, 5 tibiae had recurvatum and 3 tibiae had procurvatum. Median absolute change in sagittal plane alignment was not significantly ($P = .3$) different between reduction groups.

In the RG group, the change in torsional alignment was ≤ 5° in 5 tibiae, ≤ 10° in 2 tibiae, and > 10° in 1 tibia. In the EF group, the change in torsional alignment was ≤ 5° in 5 tibiae, ≤ 10° in 1 tibia, and > 10° in 2 tibiae. Both reduction groups had 5 tibiae with external torsion and 3 tibiae with internal torsion. Median absolute change in torsional alignment was not significantly ($P = .3$) different between reduction groups.

Discussion

We accepted our first hypothesis that the use of patient-specific pin guides restored acceptable anatomic length and facilitated acceptable fracture...
reduction as well as frontal, sagittal, and torsional alignment. Although both reduction groups had parameters with statistically significant morphologic differences from the intact tibia, these discrepancies were minor and within clinically acceptable standards.7,14,38,39

Ease or time of placement of the pin guides did not differ significantly between reduction groups, which was attributed to the similarity in guide design. Appropriately placed of the proximal pin guide was inherently easier to gauge at the time of application because of the irregular topography of the proximal tibia. Proximal guide placement did, however, require adequate elevation of the combined insertion of the sartorius, gracilis, and semitendinosus muscles as well as the popliteus and cranial tibial muscles. Appropriate placement of the distal pin guide was more difficult to gauge because the distal tibia is relatively cylindrical and lacks overt protruberances. Application of a bone-holding forceps was often required to stabilize both the proximal and distal pin guides during placement of half-pins. Pin guide placement was consistently assessed to be more efficient during the procedure on the second limb in each cadaver, which was ascribed to acquired knowledge of the extent of soft tissue dissection necessary for guide placement. Although there were statistically significant differences between the planned and actual pin guide placements, these differences were small and did not prevent clinically acceptable fracture reduction and alignment. The proximal pin guide was displaced distally, with the proximal portion displaced medially, which we ascribed to soft tissue impedance. Similarly, the distal pin guide tended to be displaced proximally with the distal portion of the guide displaced medially. Interference by soft tissues was predictable, and attempts were made in the design of the guides to minimize impedance. However, designing guides with accommodations for soft tissues can reduce the specificity of the guide fit.34 Conversely, improved fit could be attained with greater soft tissue elevation, but this approach is contrary to the principles of MIPO and could potentiate postoperative morbidity. Pin guides with smaller contact areas might reduce soft tissue interference and could potentially improve the accuracy of guide placement, particularly in areas of with unique contours such as the proximal tibia. Conversely in regions that lack distinctive topography, such as the distal tibia, a smaller pin guide contact area might potentiate inaccurate guide placement. Assessing guide designs that optimize guide fit warrants further evaluation.

We also accepted our second hypothesis that application of the 3-D printed RG was faster and less difficult than application of the EF. Assembly of the RG was straightforward, simple, and efficient. Manual reduction with the linear EF also resulted in greater variability in final alignment, compared with the fracture reduction obtained with the 3-D-printed RG. Likert-type scale responses indicated fracture reduction was easier in the RG group. Subjectively, application of the 3-D-printed RG was efficient, and the crus appeared to be well aligned in all cadavers. Although differences between reduction groups were not found, the interquartile range was larger for the EF group for all comparisons of fracture reduction, indicating greater variability within this reduction group. Application of the EF was only slightly more cumbersome than application of the RG, requiring traction of the pes and distal crus with appropriate torsional alignment. Maintenance of proper alignment as the fixation clamps were tightened contributed to longer reduction times, and adjustment of the fixator was required in 3 limbs owing to suboptimal initial torsional alignment. There was considerable variability in reduction times in the EF group, resulting in a large interquartile range, compared with that for the RG group.

The RG group consistently resulted in full restoration of tibial length, with 7 of 8 specimens actually being longer than the intact tibia, which was primarily ascribed to the proximal pin guides being placed distal to their intended location and the distal pin guides being placed a similar distance proximally. Application of the RG, which was designed assuming accurate pin guide placement, resulted in slight lengthening of the tibiae. Pin guide placement was similar in the EF group, but tibial length restoration was predicated on traction applied by the investigators, and there was a net loss of tibial length in that group. The median increase in length of 0.8 mm in the RG group represented a 0.5% change in tibial length. The EF group had median absolute change in tibial length of 2.3 mm (0.8%), with most tibiae losing length. Quinn et al.7 showed that correction of angular deformities that restored limb length to at least 91% of the length of the contralateral limb, along with other needed corrections, yielded good functional results. Francuzuski et al. reported that shorting the femur by as much as 20% can be well tolerated and that the discrepancy in limb length can be compensated by greater extension of the joints of the affected limb. Discrepancies in tibial length in the current study were comparatively minor and unlikely to affect functional outcomes.

Both reduction groups had minor frontal and sagittal translations. The EF group had a median deviation slightly greater than than the 3-mm cut-off for near anatomic reduction, although 5 of the 8 specimens had deviations ≤ 3 mm, and all discrepancies were considered clinically acceptable. Discrepancies in placement of the pin guides tended to be medial owing to the presence soft tissues on the cranial and lateral aspects of the tibia. The resulting mild translation is likely explained by the proximal pin guides being slightly more medially placed than the distal pin guides. Thus, when the RG was applied, the colinear nature of the planned pin placement would result in the distal segment being medially displaced, compared with the proximal segment. Angulation of the guide during placement could similarly result in small malalignments at the fracture site. Assessment of fracture reduction in the frontal plane revealed small valgus deviations in both groups, but the median absolute change in both
groups was \( \leq 5^\circ \). Assessment of guide placement in the frontal plane revealed that the proximal pin guides tended to be placed in a distomedial orientation, whereas the distal pin guides tended to be placed in a proximomedial orientation. Colinear pin alignment resulted in valgus deviation of the fracture segments, although the magnitude of valgus deviation in both reduction groups was unlikely to be clinically consequential.

Fracture reduction resulted in minor sagittal plane angulation, with a clinically acceptable median deviation of \( 5^\circ \) in both groups. We anticipated that the RG would produce normal tibial alignment, but comparable alignment was obtained with manual traction during EF application. Sagittal angulation was equally divided between procurvatum and recurvatum. Soft tissue interference in pin guide placement tended to result in displacement that would promote recurvatum; conversely the angled pin in each guide tended to lift the guides such that it would promote procurvatum. Visual inspection during placement along with the opposing nature of these tendencies likely contributed to the small deviations in either direction.

Torsional malalignment is a common outcome following MIPO.\(^4,14,38,39\) Torsional malalignment was minor in both reduction groups in the present study (median, \( 3^\circ \)) and would be considered clinically acceptable. Quantitative assessment of torsional alignment can be a challenge without 3-D imaging, and the minor deviations from normal noted in these tibiae may have not been discernible on traditional postoperative radiographic imaging.

This study has several limitations that prohibit us from drawing clinical conclusions. We would assume that soft tissue constraints encountered in clinical cases would make restoring length and alignment much more difficult in a live animal than in a cadaver. The effects of muscle contraction, soft tissue swelling, and early fibrosis cannot be replicated in a cadaveric study.\(^5,10\) We would suspect that restoration of tibial length in clinical cases would be more challenging with either reduction technique. Application of a printed RG might be more challenging and cumbersome than application of an EF in a live dog, particularly if surgery was performed several days after the fracture had been sustained. We did not apply a plate to definitively stabilize the simulated fractures because our aim was to evaluate the efficacy of the indirect reduction techniques in restoring normal tibial morphology. In clinical cases, a mirror image of the contralateral tibia could be 3-D printed and used to accurately precontour a plate for fracture stabilization.\(^4,16,47\) The medial aspect of the guide could be removed after application of the RG or an EF in a clinical situation to allow medial application of the plate. An epiperiosteal tunnel could be developed between the incisions made for pin guide application to perform MIPO, and application of a properly contoured plate could be further improve reduction and alignment.\(^1,5,8,9,11,20,30,37\) However, application of a plate and screws would have produced substantial artifacts on our postreduction CT images, which may have decreased the accuracy of our assessments. We assessed reduction and alignment via CT images and 3-D rendering. CT measurements of fracture reduction are more precise and accurate than typical clinical assessments of fracture reduction obtained with radiographs and allowed us to quantify small alterations from normal tibial morphology that would be unlikely to have adverse clinical consequences. Acceptable clinical fracture reduction, which has been somewhat empirically defined in both dogs and humans, allows some latitude for minor discrepancies in alignment that would be unlikely to affect functional outcomes. We applied previously reported acceptable fracture reduction criteria for minimally invasive fracture stabilization in formulating the grading system used in our study.\(^1,14,38,39\)

MIPO is predicated on restoring functional alignment through the use of indirect reduction techniques.\(^4,15\) Although neither of the assessed reduction techniques consistently restored normal tibial morphology, both yielded clinically acceptable reduction and alignment. Given our encouraging results, clinical studies to evaluate the feasibility and efficacy of virtual surgical planning based on a mirror image of the intact contralateral tibia to design and fabricate patient-specific guides to facilitate MIPO for stabilization of tibial fractures seem warranted.

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**References**


**Supplementary Material**

Supplementary materials are posted online at the journal website: avmajournals.avma.org