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A generic precurved interlocking nail is more compatible with femoral and tibial morphology than a straight nail in dogs

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OBJECTIVE
To study the morphology of canine and feline femurs and tibias in lateral radiographic projections and assess their compatibility with either a straight or a curved full-length interlocking nail (ILN).

METHODS
Lateral projection radiographs of 50 tibias and 50 femurs (10 cats and 40 dogs per bone) were used to measure the minimum and maximum radius of curvature of an ILN compatible with each bone. These radii were defined by cranial and caudal endosteal points at the proximal entry point of the nail, at the isthmus, and at the most distal point of the ILN insertion into the femoral or tibial metaphysis. These points were figured by 2 proximal circles, 2 diaphyseal circles at the isthmus, and 2 distal circles in distal metaphyses of the bones. The diameter of these circles corresponded to 75% of the medullary canal width at the isthmus of the bone.

RESULTS
An ILN with a radius between 750 and 806 mm fit 87% of all the bones reviewed. In dogs, an ILN within this radius range would fit 95% of the tibias, whereas a straight ILN would fit only 50%. For femurs, the curved ILN would fit 80% compared to 37.5% for a straight ILN. In cats, an ILN with a radius between 750 and 806 mm would fit 85% of the bones (femur, 100%; tibia, 70%), whereas a straight ILN would fit all tested bones.

CONCLUSIONS
A full-length ILN with a radius of curvature between 750 and 806 mm would fit 87% of the studied bones, whereas only 55% of them could accept a straight ILN.

CLINICAL RELEVANCE
A full-length ILN with a 750–806-mm curvature radius may provide a suitable option for treating most femoral and tibial diaphyseal fractures.

Keywords: interlocking nail, femur, tibia, dogs, cats

Femoral and tibial fractures account for 45% and 21%, respectively, of long bone fractures in dogs and cats.[1] Several surgical techniques have been described for the treatment of diaphyseal femoral and tibial fractures, with the use of an interlocking nail (ILN) being one such option.[2–15] Since the introduction of veterinary ILNs in the 1990s for managing long bone fractures, several straight-shaped models have been developed and commercialized.[4–16] However, when viewed on lateral radiographs, the tibia and femur present different shapes depending on whether only the diaphysis or the entire bone—including the metaphysis and epiphysis—is considered. The diaphysis alone appears relatively straight, particularly in cats, but when the whole bone is considered, both bones show a natural curvature. The femur has a natural diaphyseal distal procurvatum, and the tibia has a natural diaphyseal recurvatum, especially in dogs, although these features have not been widely studied.[9,10,17,18]

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These anatomical curvatures can lead to several intraoperative complications when using a straight full-length ILN for tibial and femoral fractures. In the tibia, for example, a straight nail must be inserted near the tibial plateau due to the bone's recurvatum. However, if inserted too caudally, it risks iatrogenic intermeniscal and cranial cruciate ligament injuries. Additionally, loss of the natural recurvatum can increase the tibial plateau angle (TPA). In the femur, complications can include a perforation of the femoral trochlea, and overreduction of the distal fragment, leading to loss of the distal recurvatum. Moreover, current straight ILN designs may experience mechanical stress when inserted into the medullary canal, causing slight deformations and misalignment between the locking screws or bolts and the nail holes, which can result in acute instability and poor bone healing.[8–14] Therefore, an anatomically contoured ILN that matches the natural curvature of the bone could mitigate these challenges and facilitate the treatment of more distal or proximal tibial and femoral fractures.

To our knowledge, no study has reported the anatomical morphology of the canine and feline tibia and femur investigating the use of a common curved ILN. Therefore, the objectives of this study were to study the morphology of canine and feline femurs and tibias in lateral radiographic projections and assess their compatibility with the insertion of a straight or curved full-length ILN and to assess the differences between cats and dogs. We hypothesized that (1) the positioning of the straight nail according to the whole length of the bone may not be suitable for all canine and feline femur and tibia radiographs and that (2) a curved ILN spanning from the proximal to the distal ends of the bones would fit in a higher proportion of femurs and tibias than a straight ILN. Furthermore, we anticipated morphological differences between dogs and cats.

Methods

Study population

This retrospective study included dogs and cats that underwent femoral or tibial fracture management at 3 veterinary referral centers (ONIRIS Nantes-Atlantic College of Veterinary Medicine, Centre Hospitalier Vétérinaire Pommery Anicura, and VetAgro Sup) from January 2019 through January 2024. Contralateral radiographs of the fractured bone in lateral projection and general patient data (age, breed, and weight) were collected from the electronic patients' records. Radiographs were included if they were of good quality with proper positioning and contrast and if the bones showed no visible abnormalities. Additionally, animals had to be at least 6 months old to be eligible for inclusion.

Animals were included to obtain 10 radiographs of the femur and 10 radiographs of the tibia in each of the 5 following categories: (1) cats, (2) dogs weighing less than 15 kg, (3) dogs weighing between 15 and 25 kg, (4) dogs weighing between 25 and 35 kg, and (5) dogs weighing more than 35 kg. Each group was designated either tibia (T) or femur (F), followed by a number from 1 to 5 corresponding to the weight category.

Measurement technique

All radiographs were assessed using Veterinary Preoperative Orthopedic Planning Pro software (vPOP Pro; VetSOS Education, version 2.9.5). To evaluate the compatibility of a curved or straight full-length ILN in each studied bone, 6 circles were placed at 3 specific locations: 2 at the proximal insertion site of an ILN, 2 at the isthmus of the bone, and 2 at the most distal position expected of an ILN of an appropriate diameter. For each position, 1 circle was drawn adjacent to the cranial cortex and another adjacent to the caudal cortex. Each circle diameter corresponded to 75% of the medullary canal width at the isthmus of each bone to mimic the placement of an appropriately sized ILN. All measurements were performed by 2 European College of Veterinary Surgeons residents.

Circle positioning in the femur

First, the width of the isthmus of the bone was measured. Two circles, each with a diameter equal to 75% of the isthmus width, were drawn alongside the isthmus line. One was positioned cranially (isthmus cranial circle [ICr]), adjacent to the cranial cortex, and the other was positioned caudally (isthmus caudal circle [ICd]), adjacent to the caudal cortex. Next, the proximal anatomical axis (PAA) of the femur was calculated according to a previously described method by Petazzoni and Jaeger.[19] Briefly, a first line was drawn from the proximal point of the lesser trochanter to the proximal aspect of the trochlea of the femur. The first quarter of this line was then divided into thirds, and the cranio-caudal midpoint between the cortices was determined. The PAA was defined as the straight line passing through these midpoints **Supplementary Figure S1**.[19] Then, at the level of the lesser trochanter, a line was drawn perpendicular to the PAA of the femur. Two circles of the same diameter were positioned along this line, 1 adjacent to the cranial cortex (proximal cranial circle [PCr]) and the other adjacent to the caudal cortex (proximal caudal circle [PCd]). Finally, 2 distal circles (distal cranial circle [DCr] and distal caudal circle [DCd]) were placed along a line connecting the proximal aspect of the trochlear grove and the proximal aspect of the femoral condyle. This line represented the expected distal position of an ILN **(Figure 1)**.

Circle positioning in the tibia

Similar to the femur, the width of the isthmus of the bone was measured, and 2 circles corresponding to 75% of its width were placed along the isthmus line (ICr and ICd). Next, a line was drawn connecting the cranial aspect of the tibial plateau and the patellar tendon insertion (line 1). A second line (line 2) was drawn perpendicular to line 1 at its midpoint. A circle was placed where line 2 met the tibial cortex

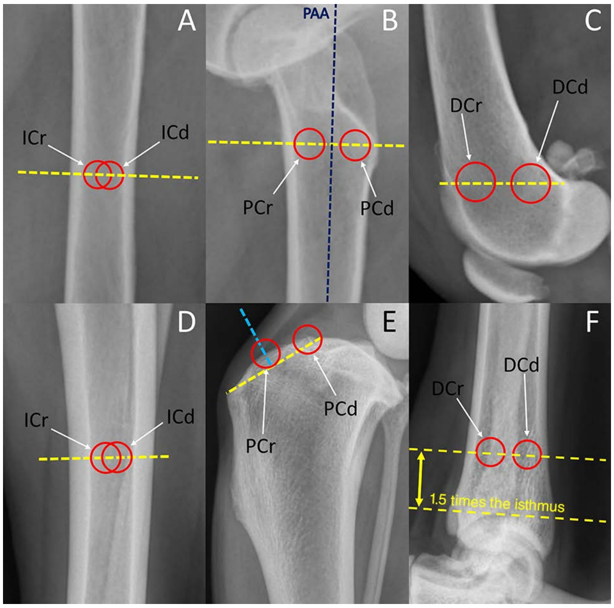

Figure 1—Lateral radiographic projection of a dog femur and tibia showing the placement of the 6 circles described. A—Two circles along the isthmus line (isthmus cranial circle [ICr] and isthmus caudal circle [ICd]). B—Two proximal circles on a line perpendicular to the proximal anatomical axis (PAA) at the level of the lesser trochanter (proximal cranial circle [PCr] and proximal caudal circle [PCd]). C—Two distal circles on a line connecting the proximal aspect of the trochlear groove to the proximal aspect of the femoral condyle (distal cranial circle [DCr] and distal caudal circle [DCd]). D—Two circles along the isthmus line (ICr and ICd). E—One proximal circle placed cranially to the tibial plateau (PCd) and a second proximal circle (PCr) where the blue line meets the cortex. This blue line was drawn perpendicular to the yellow line at its mid distance, between the patellar tendon insertion to the cranial aspect of the tibial plateau. F—Two distal circles on a line parallel to a line tangent to the talocrural joint with a distance of 1.5 times the isthmus of the bone (DCr and DCd).

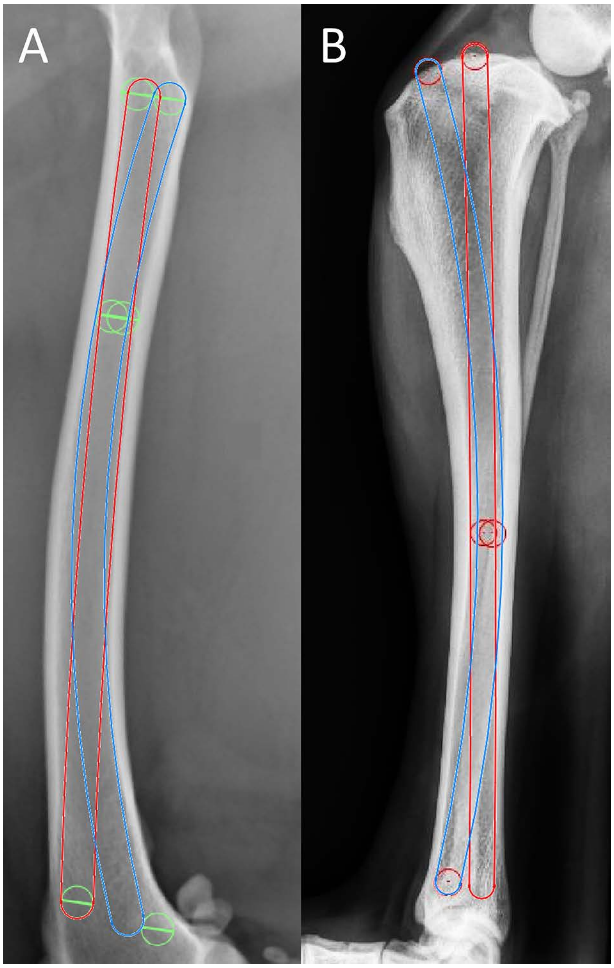

Figure 2—Radius of curvature measurement of the interlocking nail (ILN) inserted into a canine femur (A) and tibia (B). The blue nail profile corresponds to the minimum radius of curvature measurement and the red one to the maximum radius of curvature possible for the tested bone.

(PCr), and another circle was placed on line 1, adjacent to the tibial plateau (PCd). These circles corresponded to the most appropriate cranial and caudal proximal insertion points for an ILN. Distally, 2 circles were placed on a line at a distance corresponding to 1.5 times the width of the isthmus from the tarsocrural joint (DCr and DCd). This line represented the expected distal position of an ILN inserted into the tibia (Figure 1).

Radius of curvature measurement

The borders of the medullary canal were identified with computer-aided design software (SolidWorks; Dassault Systèmes, version 2024). For each bone, 2 ILNs with the same diameter passing by the preplaced circles were drawn to calculate their respective minimum and maximum radius of curvature as shown in **Figure 2**. If the ILN could not be entirely contained within the medullary canal, the nearest circle to the target was used to ensure full ILN containment. For the femur, the minimum radius of curvature was obtained by connecting the circles PCd, ICr, and DCd and the maximum radius of curvature by connecting the circles PCr, ICd, and DCr. For the tibia, the minimum radius of curvature was obtained by connecting the circles PCr, ICd, and DCr and the maximum radius of curvature by connecting the circles PCd, ICr, and DCd.

An ILN with a radius of curvature between the calculated minimal and maximal radius of curvature values was deemed to fit in the tested bone. The radius was expressed in millimeters. A straight ILN has a radius of curvature of infinity. Consequently, any ILN with a radius of curvature greater than 5,000 mm was considered straight. An intraclass correlation coefficient (ICC) was used to evaluate the correlation of the maximum and minimum radius of curvature measurements performed by the 2 observers in the tibia and the femur. For each bone, the mean of the 2 observers' measurements was calculated for both the minimum and maximum values.

Results

Femur

The median weight of the F1 group (cats) was 4 kg. All of these cats were domestic shorthairs. The median weight of the F2 group (dogs < 15 kg) was 9 kg. In this group, there was 1 Fox Terrier, 1 Beagle, 1 Entlebucher Mountain Dog, 1 Cocker Spaniel, 1 King Charles Spaniel, 1 Lhasa Apso, 1 Chihuahua, 1 Mexican Hairless Dog, and 2 crossbreed dogs. The median weight of the F3 group (dogs 15 to 25 kg) was 21 kg. This group was composed of 1 Labrador Retriever, 1 Border Collie, 1 Beagle, 1 Belgian Shepherd, 1 Boxer, 2 Australian Shepherds, 2 American Staffordshire Bull Terriers, and 1 crossbreed dog. The median weight of the F4 group (dogs 25 to 35 kg) was 29 kg. This group included 1 Labrador Retriever, 1 Golden Retriever, 1 Collie, 1 Boxer, 1 American Staffordshire Bull Terrier, 1 Australian Shepherd, 1 Belgian Shepherd, and 3 crossbreed dogs. Finally, the median weight of the F5 group (dogs > 35 kg) was 40 kg. In this group, there was 1 Akita Inu, 1 Golden Retriever, 1 Labrador, 1 German Shepherd, 1 Bernese Mountain Dog, 1 Newfoundland, 1 Bordeaux Mastiff, 1 Drahthaar, 1 Cane Corso, and 1 Beauce Shepherd.

When dogs and cats were combined, a curved full-length ILN with a radius of curvature between 750 and 806 mm would fit the highest number of bones from the studied population, successfully

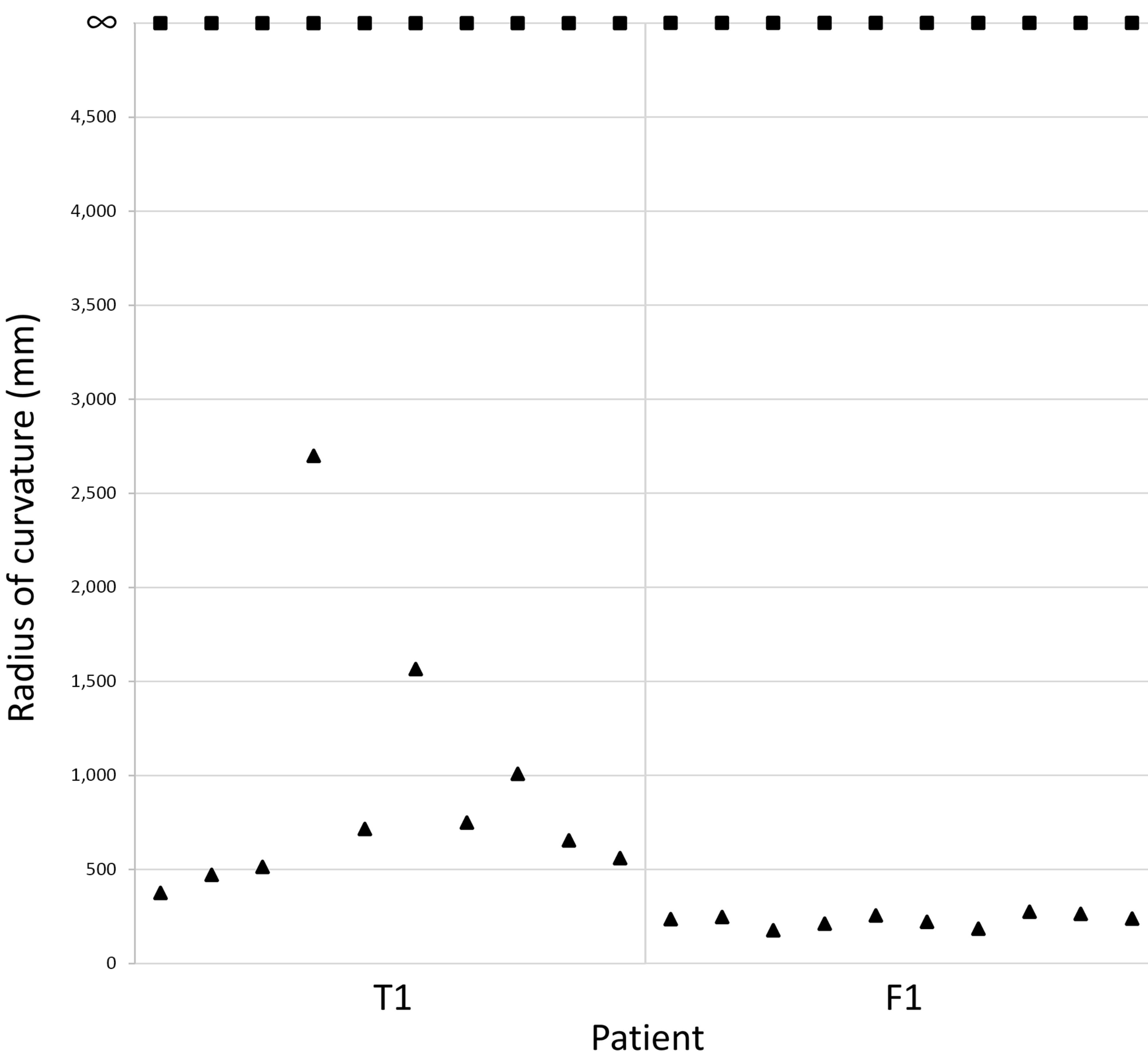

Figure 3—Results of the maximum and minimum radius of curvature measurements for the feline tibias (T1) and femurs (F1). The x-axis corresponds to each patient and the y-axis to the radius of curvature expressed in millimeters. A radius of curvature over 5,000 mm was considered to be infinite, corresponding to a straight nail. The triangle indicates the minimum radius of curvature, and the square indicates the maximum radius of curvature of the tested bone. An ILN with a radius of curvature between the 2 values (triangle and square) will fit the tested bone.

fitting 84% of femurs, whereas a straight full-length ILN would fit only 50%. In cats, both the straight and curved full-length ILNs with a radius of curvature between 750 and 806 mm would fit 100% of the femurs **(Figure 3)**. In dogs, a curved full-length ILN with a radius of curvature between 750 and 806 mm would fit 80% of femurs, whereas a straight ILN extending to the metaphyses would fit only 37.5% of canine femurs **(Figure 4)**. Details of the results for the femurs in each group are shown in **Table 1**.

Eight dogs (4 from the F2 group, 2 from the F4 group, and 2 from the F5 group) had an excessive procurvatum in their femurs, preventing the placement of either a straight ILN or a curved ILN with a radius between 750 and 806 mm. These dogs had a low minimum and maximum radius of curvature,

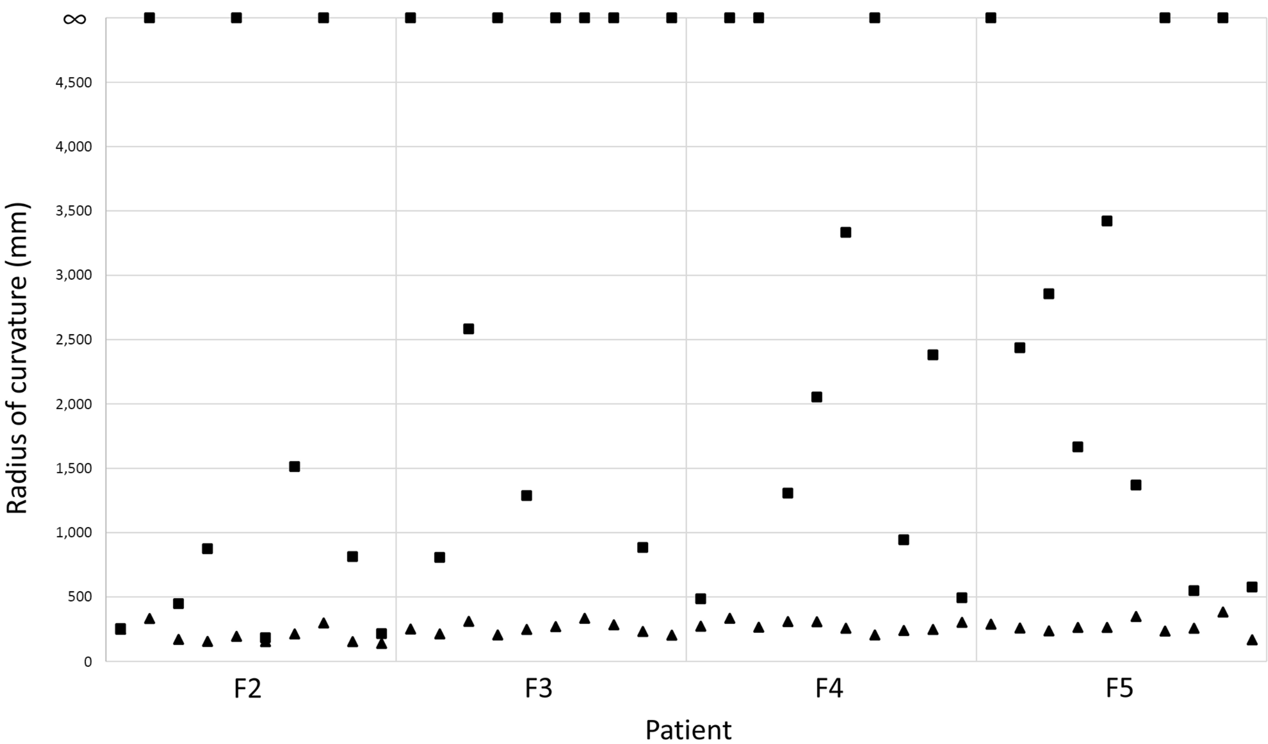

Figure 4—Results of the maximum and minimum radius of curvature measurement for the canine femurs. The x-axis corresponds to each patient and the y-axis to the radius of curvature expressed in millimeters. A radius of curvature over 5,000 mm was considered to be infinite. The triangle corresponds to the minimum radius of curvature of the tested bone, and the square corresponds to the maximum radius of curvature of the tested bone. An ILN with a radius of curvature between the 2 values (triangle and square) will fit into the tested bone. F2 = Dogs weighing less than 15 kg. F3 = Dogs weighing between 15 and 25 kg. F4 = Dogs weighing between 25 and 35 kg. F5 = Dogs weighing more than 35 kg.

Table 1—Median minimum and maximum radius of curvature of a femoral interlocking nail (ILN) in the different femoral and tibial groups.

Group	Median minimum radius of curvature expressed in millimeters (range)	Median maximum radius of curvature expressed in millimeters (range)	Percentage of bones where a curved ILN (750–806 mm) fits (%)	Percentage of bones where a straight ILN fits (%)
F1 (cats; n = 10)	237 (175–274)	5,000 (5,000–5,000)	100	100
F2 (< 15 kg; n = 10)	182 (139–333)	844 (184–5,000)	60	30
F3 (15–25 kg; n = 10)	249 (203–334)	5,000 (806–5,000)	100	60
F4 (25–35 kg; n = 10)	269 (206–335)	2,217 (486–5,000)	80	30
F5 (> 35 kg; n = 10)	260 (167–383)	2,646 (549–5,000)	80	30
T1 (cats; n = 10)	685 (376–5,000)	5,000 (5,000–5,000)	70	100
T2 (< 15 kg; n = 10)	227 (60–463)	1,382 (157–5,000)	90	40
T3 (15–25 kg; n = 10)	315 (189–432)	3,043 (1,001–5,000)	100	40
T4 (25–35 kg; n = 10)	313 (221–545)	2,225 (438–5,000)	90	30
T5 (> 35 kg; n = 10)	410 (328–526)	5,000 (2,478–5,000)	100	90

Data presented as median, range, and the percentage of bones where an ILN fits.

F1 = Cats. F2 = Dogs weighing less than 15 kg. F3 = Dogs weighing between 15 kg and 25 kg. F4 = Dogs weighing between 25 kg and 35 kg. F5 = Dogs weighing more than 35 kg. T1 = Cats. T2 = Dogs weighing less than 15 kg. T3 = Dogs weighing between 15 kg and 25 kg. T4 = Dogs weighing between 25 kg and 35 kg. T5 = Dogs weighing more than 35 kg.

with narrow ranges from 139 to 448 mm for the F2 group, 273 to 494 mm for the F4 group, and 372 to 576 mm for the F5 group.

Tibia

The median weight of the T1 group (cats) was 5 kg. All of these cats were domestic shorthairs. The median weight of the T2 group (dogs < 15 kg) was 10 kg. In this group, there was 1 Fox Terrier, 1 Beagle, 1 Corgi, 1 Maltese, 1 Cairn Terrier, and 5 crossbreed dogs. The median weight of the T3 group (dogs 15 to 25 kg) was 21 kg. This group was composed of 1 Bull Terrier, 1 Australian Shepherd, 1 Bavarian, 1 Basset, 1 American Staffordshire Terrier, 2 Beagles, and 3 Spaniels. The median weight of the T4 group (dogs 25 to 35 kg) was 29 kg. This group included 1 Labrador Retriever, 1 Golden Retriever, 1 Pointer, 1 American Staffordshire Bull Terrier, 1 Spaniel, 1 Belgian Shepherd, 1 Rottweiler, 2 Boxers, and 1 crossbreed dog. Finally, the median weight of the T5 group (dogs > 35 kg) was 43 kg. In this group, there was 1 Akita Inu, 1 Tatra Shepherd, 1 Bernese Mountain Dog, 2 Belgian Shepherds, and 5 crossbreed dogs.

When dogs and cats were combined, a curved full-length ILN with a radius of curvature between 750 and 806 mm would fit 90% of tibias, whereas a straight full-length ILN would fit only 60%. In cats, a curved ILN with a radius of curvature between 750 and 806 mm would fit only 70% of tibias, whereas a straight ILN would fit 100% (Figure 3). In dogs, a curved ILN with a radius of curvature between 750 and 806 mm would fit 95% of the bones, whereas a straight ILN would fit only 50% **(Figure 5)**. Details of the results for the tibias in each group are shown in Table 1.

Two crossbreed dogs, 1 from the T2 group and 1 from the T4 group, had an excessive recurvatum of their tibias, preventing the placement of either a straight ILN or a curved ILN with a radius between 750 and 806 mm. These dogs had a low minimum and maximum radius of curvature with narrow ranges, with the T2 dog's radius ranging from 60 to 157 mm and the T4 dog's radius ranging from 330 to 438 mm.

One cat (tibia 7 in the T1 group) had a procurvatum in its tibia, meaning that this animal had an ILN whose minimum radius of curvature was in the opposite direction compared to the other tibias in the study. The minimum radius of curvature of the ILN corresponded to 750 mm in this cat. This was the only case with this particularity in the studied population.

Overall results

When femurs and tibias were considered together, a straight ILN spanning from the proximal

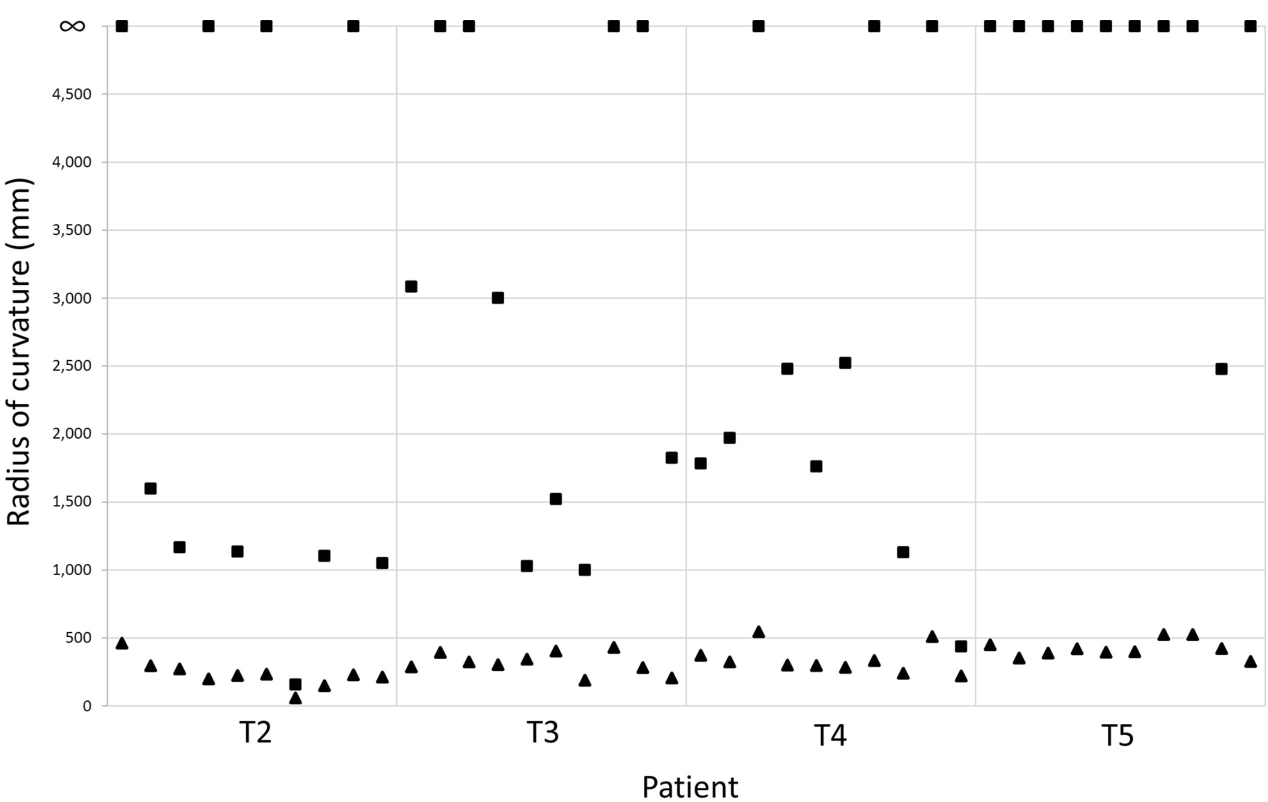

Figure 5—Results of the maximum and minimum radius of curvature measurement for the canine tibias. The x-axis corresponds to each patient and the y-axis to the radius of curvature expressed in millimeters. A radius of curvature over 5,000 mm was considered to be infinite, corresponding to a straight nail. The triangle indicates the minimum radius of curvature, and the square indicates the maximum radius of curvature of the tested bone. An ILN with a radius of curvature between the 2 values (triangle and square) will fit the tested bone.

to the distal ends of the bones would fit only 55% of them. An ILN with a radius of curvature between 750 and 806 mm would fit the highest number of bones from the studied population, successfully fitting 87% of all bones evaluated. Specifically, a curved ILN with a radius in this range would fit 85% of feline bones and 87.5% of canine bones. A straight full-length ILN would fit all feline bones but only 43.75% of all canine bones. The ICC was excellent for both the minimum and maximum radius of curvature measurements in the femur and the tibia, with ICCs of 0.931 and 0.901 for the femur and 0.995 and 0.913 for the tibia, respectively.

Discussion

In this study, feline and canine femurs and tibias in lateral radiographic projection were evaluated to determine the most appropriate generic morphology of an ILN that best conforms to the natural anatomic shape of those bones. Today, the vast majority of the commercially available ILNs are straight. Our results showed that a full-length ILN with a radius of curvature between 750 and 806 mm would fit 87% of all the studied bones compared to only 55% with a straight full-length ILN. A curved ILN, filling 75% of the bone at the isthmus, also respected the natural femoral procurvatum and tibial recurvatum, making it anatomically appropriate for treating diaphyseal fractures of these bones except in the 30% of the studied feline tibias that accepted only a straight nail. Thus, our first hypothesis was confirmed.

Over the past few years, minimally invasive osteosynthesis (MIO) has become increasingly popular. This technique does not expose the fracture site, thus preserving soft tissue and fracture hematoma, which promotes healing. While some studies[20] have reported rapid fracture healing or time to union of 30 to 40 days, others have shown no difference in healing time between MIO and open surgeries.[21,22] As MIO gained popularity, the use of ILNs became increasingly widespread. Interlocking nails have been shown to offer greater stiffness in compression and 4-point bending and greater resistance to failure in compression, torsion, and 4-point bending than locking compression plates.[2] One key advantage of intramedullary devices, such as IM pins and ILNs, is that they aid in aligning bone fragments during minimally invasive procedures.[18] An ILN with a morphology similar to the fractured bone can help reduce the fracture by following the anatomical shape of the bone. In addition, a curved ILN can be inserted deeper into the metaphysis and/or epiphysis while preserving bone anatomy, allowing the treatment of more proximal and distal fractures compared to a straight ILN.

Our study determined that an ILN with a radius of curvature between 750 and 806 mm is the most appropriate shape, fitting 87% of the bones tested. In contrast, only 55% could accommodate a straight ILN, validating our second hypothesis. Additionally, the use of a common radius of curvature would allow surgeons to use a single aiming device for most femoral and tibial fractures in dogs and cats.

The study also revealed significant differences between dogs and cats. Cats have straighter diaphysis than dogs. All feline bones tested could have received a straight ILN compared to only 43.75% for dogs. Only 70% of feline tibias could have received a curved ILN with a radius of curvature between 750 and 806 mm compared to 95% of canine tibias. In feline femurs, all bones could have received a curved ILN with a radius between 750 and 806 mm compared to 80% of canine femurs. While these findings confirm our third hypothesis, the study population included only 20 cats compared to 80 dogs, suggesting that further research is needed to investigate these differences more thoroughly.

One study[23] concerning the morphometry of the canine femur reported an anterior bow in a Greyhound's femur at 35% of the biomechanical length more pronounced in dogs than in humans. Another study[24] reported a bow angle of 18.3° ± 2.02° in a dog femur. Textbooks state that the femur body (corpus femoris) is straight proximally and cranially curved distally.[25] However, there is a difference in the anatomy of the diaphysis between dogs and cats. Cats seem to have straighter diaphysis than dogs.[26] Cabassu[27] evaluated the curvatum of the femur after the use of MIO techniques for femoral fracture osteosynthesis. A mean angle of 4.2°, measured between a tangential line to the proximal cortex and a second tangential line to the distal cortex on the mediolateral view of the intact femur, was reported.[27] Cabassu[27] also measured a difference of −5.6° between procurvatum values of the operated femur compared to the contralateral healthy femur. An excessive procurvatum of the distal part of the femur—in other word, a more caudally curved femur—may lead to patella alta and increase the risk of patellar luxation. Conversely, an over-reduction of the femoral trochlea, and thus a reduced distal procurvatum, may not have adverse clinical consequences.[12] However, there is no data available in the literature about the potential consequences of a modified curvatum alignment of the femur. Regarding the tibia, it is widely accepted that there is a natural recurvatum of the bone,[12] but to the authors' knowledge no veterinary studies have investigated this point.

The recurvatum located in the distal part of the femur may explain some perioperative complications encountered when inserting a straight ILN. For example, inserting a straight ILN from proximal to distal may lead to the nail penetrating the trochlear groove. To avoid this complication, the distal fragment can be over-reduced to allow a deeper nail penetration into the distal epiphysis of the femur.[12,26] A curved ILN inserted from the proximal to the distal end of the femur would better conform to the natural procurvatum, positioning its distal extremity more caudally in the distal metaphysis/epiphysis. This caudal and distal position in the femoral distal extremity may reduce the risk of any iatrogenic damage to the trochlear groove while providing a better bone purchase for the locking screws.

In the tibia, the insertion site of an ILN is located cranially to the tibial plateau to avoid iatrogenic damage to the intermeniscal ligament and the cranial cruciate ligament footprint. Using a straight ILN may lead to a loss of the natural recurvatum of the bone, potentially increasing the TPA. A steeper TPA has been associated with cranial cruciate ligament rupture,[28] but the role of the TPA in this condition remains controversial. Therefore, a potential advantage of a curved ILN is that it can restore the natural recurvatum of the tibia, thereby preserving the initial TPA and reducing the risk of damaging the cranial cruciate ligament footprint with a more cranial insertion site.[29] In addition, there is an asymmetrical muscle distribution around the tibia. The gastrocnemius muscle, located caudally to the tibia, creates an eccentric caudal compression force, leading to a sagittal bending moment.[12,29] One ex vivo biomechanical study[29] demonstrates the mechanical benefits of a cranially bent ILN in a clinically relevant tibial fracture model. Their results showed that a cranially bent ILN resisted nearly 20% greater maximum compressive load compared to a straight ILN in a tibial fracture gap model. It has been suggested that bending a straight ILN to match the natural recurvatum of the tibia may be beneficial.[29] This approach allows the ILN to conform to the individual anatomic variations of each bone, as some dogs exhibit a greater recurvatum angle, and it also aids in the apposition of the bone fragments along the nail shaft.[29] However, this technique requires precise preoperative planning to bend the ILN into the appropriate angle, which can be time consuming. Finally, the bent ILN will not be aligned with the aiming device that is designed for a straight ILN. As a result, intraoperative fluoroscopy may be necessary to ensure the correct placement of the locking implants through the ILN, increasing the need for radiation safety precautions during surgery.

We used a 3-point system to draw an ILN in the medullary cavity of the bone, following a precise protocol to minimize interobserver measurement discrepancies. The drawn points were defined to closely approximate the position of an ILN in a clinical setting. For the femur, the insertion point for a normograde ILN placement is located at the trochanteric fossa.[30] We chose to use the lesser trochanter to have a reference point close to the trochanteric fossa on the lateral projection of the radiographs. For the tibia, the insertion point of an ILN is located cranially to the tibial plateau.[31] Thus, the position of the proximal caudal circle of the tibia corresponded to the most caudal possible insertion point of an ILN. Previous studies[32] have reported interobserver variability in identifying the proximal extremity of the tibial plateau for calculating the TPA. In our study, there is an excellent interobserver agreement, with the ICC exceeding 0.9 for the measurement of the minimum and maximum radius of curvature of an ILN in both the tibia and the femur, but this point still represents a limitation of our study. Other limitations of this study are related to its radiographic design. We only evaluated the sagittal morphology of the bones. In the frontal plane, the shape of the femoral diaphysis is relatively straight, whereas in the tibia there is a proximal diaphyseal varus and a distal diaphyseal valgus. It remains true that some individuals may present a specific femoral or tibial morphology in the frontal plane and therefore may require an individually customized ILN. This can be an area for future research. A 3-D rendering of the tibia and femur using CT imaging could have provided a more accurate description of the shape of the entire medullary canal. While we evaluated 50 femurs and tibias from different breeds and sizes, our sample may not be fully representative of the entire canine and feline population, given the extreme anatomic variations in some breeds, despite our efforts to include a diverse range of breeds in each canine group.

Our results showed that some animals exhibited extreme anatomical variations. Ten dogs (2 tibias and 8 femurs) in our population showed a low and narrow range between the minimum and maximum radius of curvature measured, suggesting a potential breed-specific effect. A previous study[33] comparing the anatomy of the humerus between brachycephalic dogs and nonbrachycephalic dogs found that there was a difference in the geometry of the bone between the 2 groups of dogs. Such breed-related influences may also be considered for femur and tibia anatomy but were beyond the scope of our study. Notably, 1 cat (tibia 7 in the T1 group) exhibited a tibia with a curvature opposite to the standard, indicating a procurvatum.

Diaphyseal fractures of the humerus can also be treated with ILNs in dogs and cats.[13,16] The humerus was shown to present a shaft curvature angle of $7.9° \pm 2.1°$ in nonbrachycephalic dogs,[33] and a second study[34] reported a mean shaft curvature of the humerus of 20°. Further research could apply our approach to examine humeral morphology and assess whether a similarly generic curved ILN is suitable for the humerus in dogs and cats.

In conclusion, an ideal ILN with a common radius of curvature for all canine and feline tibias and femurs does not exist. However, a full-length ILN with a radius of curvature between 750 and 806 mm would fit 87% of the bones studied, whereas only 55% of them could accept a straight full-length ILN. Finally, only 10% of the bones we evaluated would require individually customized ILNs.

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Disclosures

Dr. Gauthier and Dr. Cachon participated in the initial development of the precontoured anglestable interlocking nail (CAS-ILN) without royalties. Dr. Gauthier and Dr. Cachon run continuing education courses related to the CAS-ILN implant.

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Supplementary Materials

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