Complex angular and torsional deformities (distal femoral malunions)

Preoperative planning using stereolithography and surgical correction with locking plate fixation in four dogs

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Keywords

Angular limb deformity, corrective osteotomy, stereolithography, preoperative planning

Summary

Objective: To describe the surgical technique of complex distal femoral deformity correction with the aid of stereolithography apparatus (SLA) biomodels, stabilized with locking plate fixation.

Methods: Full-size replica epoxy bone biomodels of the affected femurs (4 dogs/ 5 limbs) were used as templates for surgical planning. A rehearsal procedure was performed on the biomodels aided by a guide wire technique and stabilized with locking plate fixation. Surgery performed in all dogs was guided by the rehearsal procedure. All pre-contoured implants were subsequently used in the definitive surgical procedure with minimal modification.

Results: All dogs had markedly improved, with near normal functional outcomes; all but one had a mild persistent lameness at the final in-hospital follow-up examination (mean: 54.4 weeks; range: 24–113 weeks after surgery). All femurs healed without complications (mean: 34 weeks, median: 12 weeks; range: 8–12 weeks for closing osteotomies, and 26–113 weeks for opening wedge osteotomies). Long-term follow-up examination (mean: 28.6 months; range: 5–42 months) revealed all but one owner to be highly satisfied with the outcome. Complications were observed in two dogs: prolonged tibiotarsal joint decreased flexion that resolved with physical therapy. In one of these dogs, iatrogenic transection of the long digital extensor tendon was repaired, and the other had a peroneal nerve neurapraxia.

Clinical significance: Stereolithography apparatus biomodels and rehearsal surgery simplified the definitive surgical corrections of complex femoral malunions and resulted in good functional outcomes.

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Introduction

A number of methods have been utilized in the dog for both pre-surgical planning and surgical correction of angular limb deformities (1–5). Some angular limb deformities are typically challenging to assess radiographically due to multi-planar torsional and angular deformities, making accurate measurements difficult to obtain (3, 5, 6). In addition, the femur is particularly difficult to assess as the frontal and sagittal plane orientation can easily be masked by the inability to easily locate the hip joint orientation in the presence of torsion or multiplanar deformities. As such, this combination of factors can reasonably define such deformities as complex, although we realize this is a subjective definition. Software manipulation of computed tomography (CT) data has been described in humans, and also has been used to allow more accurate assessment in the dog (5, 7-11). However, even with these data and techniques, the surgical planning of such deformities remains difficult to accurately assess (5, 6). Moreover, translating this information from the radiographs and the CT to the patient at the time of the surgical procedure can be difficult in both dogs and humans (5, 9, 12, 13).

Various methods of three-dimensional (3D) printing have been utilized to reproduce anatomical structures for medical use in both human and veterinary medicine (14). Stereolithography is a rapid prototyping technology that allows the creation of solid, 3D objects obtained

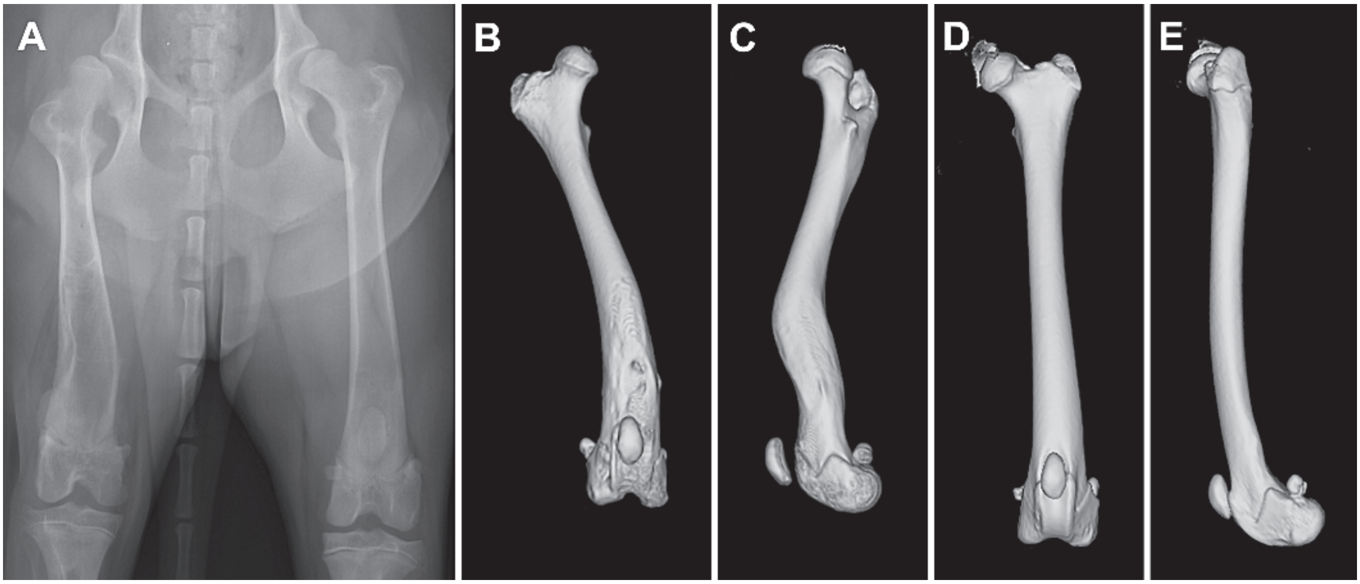

Figure 1 **A)** Ventrodorsal pelvis radiograph preoperatively in a nine-month-old castrated male mixed breed dog (limb 5) with a biapical deformity of the femur; note the malposition of the hip joint. **B, C)** Craniocaudal and lateral three-dimensional reconstruction from computed tomography data that shows the right femoral angular and torsional femoral deformity: proximal procurvatum with distal recurvatum and valgus malalignment; also notice the proximal femoral torsion (position of femoral head, neck and greater trochanter); **D, E)** compare with the opposite normal femur.

from CT data with computer aided design (CAD) software, and as such the ability to create accurate full-size anatomical models of the bone. The use of stereolithography has been reported in veterinary medicine to assist correction of antebrachial deformities, pelvic limb deformity, and total knee arthroplasty (3, 5, 6, 15). Accurate pre-planning with 3D biomodels in humans has been reported to translate into a more definite surgical process with increased knowledge of the intricacies of the procedure, improved surgeon confidence, increased surgical efficiency, and reduced anaesthesia time (16).

The purpose of this study was to describe the surgical techniques in complex distal femoral deformity corrections with the aid of stereolithography apparatus (SLA) biomodels, and stabilized with multiple titanium locking plate fixation in four dogs (5 limbs). Our aims were to evaluate the use of SLA biomodels to facilitate the pre- and intra-operative surgical plan, and as a result, obtain appropriate realignment of the affected limb and an improved functional outcome without major complications. A further aim was to evaluate healing after multiple titanium locking plate fixation.

Materials and methods

The study was conducted in a manner consistent with the US National Institutes of Health "Guide for the Care and Use of Laboratory Animals" and the Animal Welfare Acts (US PL 89–544; 91–579; 94–279).

Criteria for case selection

Medical records of four client owned dogs (5 limbs) with severe distal femoral malunion and treated at the Cummings School of Veterinary Medicine at Tufts University using SLA planning and titanium locking

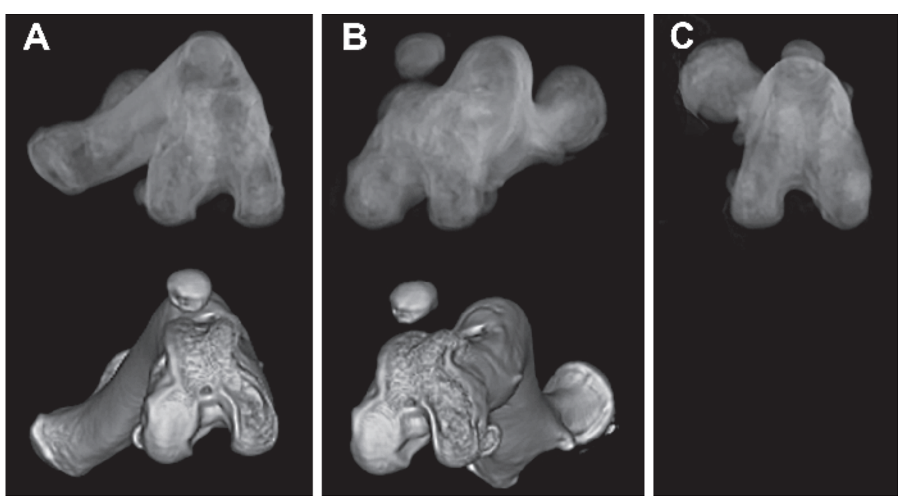

Figure 2 Skyline view (limb 5) three-dimensional (3D) reconstruction from computed tomography (CT) data that demonstrates the inability to assess the femoral torsion of the right femur **(A and B)**, as the anteversion of the femoral head and neck, and position of the femoral condyles cannot be viewed simultaneously (upper views are radiographic opacity images, while the lower views are bone opacity images so as to more easily interpret the bone conformation); **C)** compare with opposite normal femur. Preoperative CT data and further software image manipulation cannot identify the specific areas of deformity, much less quantify them with any degree of accuracy, as these remain two-dimensional images of a 3D structure.

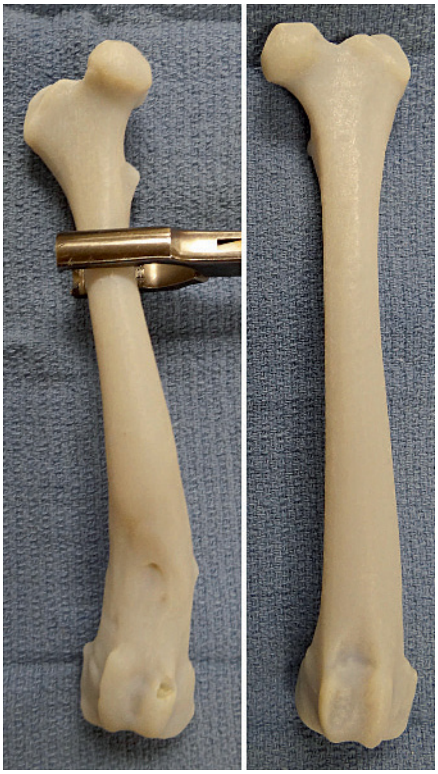

Figure 3 Stereolithographic epoxy biomodels of the right and left (normal) femurs (limb 5).

plates (January 2007 - June 2012) were reviewed. Signalment, orthopaedic examination, assessment of pelvic limb use as a result of the obvious angular or torsional deformity observed (varus/valgus, pro-/recurvatum, femoral torsion), patellar stability, and any compensatory tibial conformational abnormalities (angulation and torsion) were recorded. The preoperative anatomical lateral distal femoral angle (aLDFA) and the medial proximal tibial angle (MPTA)[a] were determined retrospectively before 2008, and prospectively after 2007 (17, 18).

Surgical planning

Radiographic and computed tomography evaluation

Ventrodorsal and lateral pelvic radiographs were obtained together with craniocaudal

a Note that in the tibia, the mechanical and anatomical tibial axes are identical; therefore, the convention of identifying either the mechanical or anatomical axis is not used, and the angles in the frontal plane are defined simply by MPTA and MDTA.

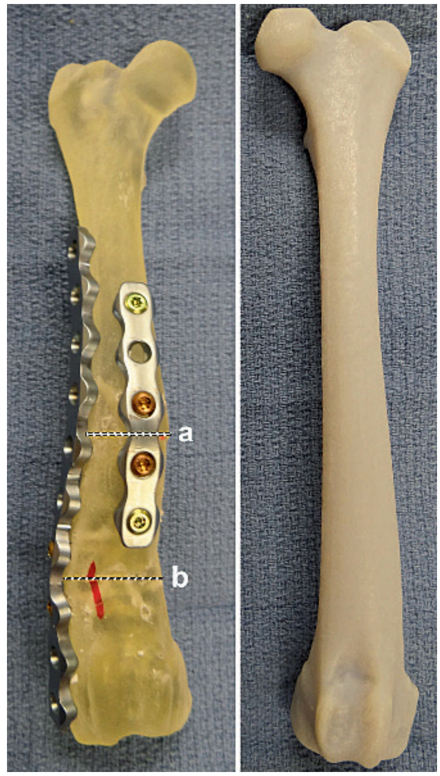

Figure 4 Stereolithographic epoxy biomodels of the right and left (normal) femurs after rehearsal surgery on the right femur (limb 5). The torsional deformity has been corrected with a transverse osteotomy at (a) and spanned with a 5-hole ALPS (advanced locking plate system) 10 cranially; the distal valgus and recurvatum have been corrected with a second biplanar cuneiform (medial and caudal) closing wedge osteotomy at (b). Both osteotomies were spanned laterally with a 10-hole ALPS 10 (a medially applied plate was not placed at this time).

and mediolateral radiographs of the femur and tibia if indicated (▶Figure 1A). A CT scan[b] (120 kv, 300 mAs; sw 4.0-mm, index 2-mm; sharp algorithm) was also obtained of both hindlimbs (▶Figure 1B-E, ▶Figure 2). The digital CT images were sent to a service provider[c] for further processing.

Preplanning (SLA biomodels)

Epoxy mono-colour SLA biomodels of the femurs were manufactured[c] with an epoxy resin (▶Figure 3). The aLDFA and femoral torsion were recorded directly from the SLA biomodels and compared directly to the opposite normal limb in order to match the mirrored orientation; in the one case with bilateral deformities, a comparison was made to anatomical specimens from a dog of similar size. Guide wires were used to assist in determining the proper spatial orientation and also the corrections to be made (▶Appendix I: available online at www.vcot-online.com). Corrective osteotomy with plate fixation was performed as a rehearsal procedure (▶Figure 4). The pre-contoured plates were removed and sterilized in preparation for the definitive surgical procedure.

b Picker PQ 5000 spiral scanner: Picker International Inc., Cleveland, OH, USA
c ProtoMED®, Westminster, CO, USA

Definitive surgical technique

Dogs were positioned in dorsal recumbency with the affected limb aseptically prepared to the dorsal midline. Perioperative cefazolin sodium (22 mg/kg) was administered intravenously every two hours throughout the duration of the procedure. A standard lateral approach to the femur was performed combined with a lateral parapatellar arthrotomy (and extended craniomedially and distally to approach the medial aspect of the tibia if necessary). A tibial tuberosity osteotomy was performed using a sagittal saw, and the tuberosity reflected both proximally and medially in order to gain full bilateral exposure to the stifle joint and femoral condyles.

The definitive surgical procedure was repeated in the dog as performed with the rehearsal procedure (▶Appendix II: available online at www.vcot-online.com). If necessary, the degree of correction was modified due to soft-tissue limitations; clinical judgment and gross evaluation dictated the deviation from the original surgical plan. Preoperative angle measurement, guide wire placement and final visual assessment were used together for final evaluation of limb alignment (12).

Compensatory abnormalities were also present in the adjacent tibias in all of the dogs (only one tibia in the dog with bilateral deformities). Evaluation and planning of the tibias were performed from orthogonal radiographs, CT data, or both as previously described; however, when torsional as well as angular deformity was present, no preoperative radiographic quantification of the frontal plane deformity was

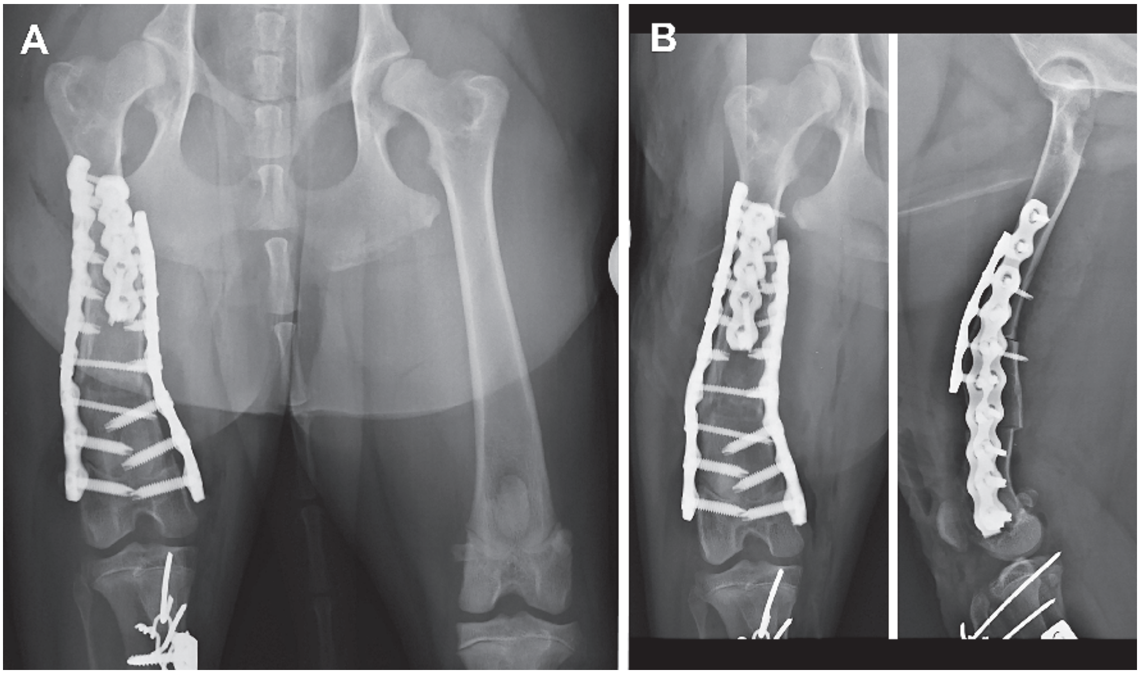

Figure 5
A) Immediate postoperative ventrodorsal pelvic radiographic image demonstrating appropriate femoral alignment and hip position as compared to the normal, unaffected femur. **B, C)** Immediate postoperative craniocaudal and lateral radiograph of the right femur (limb 5) demonstrating appropriate femoral alignment (compare with ►Figure 1 B and C; also compare with rehearsal surgery in ►Figure 4).

possible (19). Gross estimation was obtained and further angular correction was planned intra-operatively using the guidewire technique to determine joint orientation (19). Tibial torsion was corrected, regardless of the type of osteotomy performed, by visual assessment and re-alignment of the pes with the patellar ligament. The SLA biomodels were not used for these assessments.

After completion of the corrective osteotomies, the stifle joint was evaluated independently. Any excessive peripatellar fibrous connective tissue was removed. Patellar position and trochlear sulcus were evaluated. Fascial release, tuberosity transposition and sulcoplasty were performed as needed to ensure re-alignment of the quadriceps mechanism and patellar position within the sulcus. The tibial tuberosity was re-attached with multiple Kirschner-wires and a figure-of-right tension-band wire. Soft tissues were closed in a routine fashion.

Postoperative assessment

Radiographs of the affected femur together with the tibia, if necessary, were obtained (►Figure 5). Postoperative aLDFA, MPTA and medial distal tibial angle (MDTA) were determined as previously indicated (17, 18). Final limb alignments were also evaluated grossly.

Postoperative Care

Postoperative analgesics were administered at the discretion of the primary surgeon, which included either parenteral hydromorphone, fentanyl continuous infusion, or methadone for the first two to four days, then followed by parenteral buprenorphine for one to two days, oral tramadol, or both until discharge (the particular regime used was based on the hospital protocol at the time, and not by any perceived specific need for these dogs, which did not differ from the routine postoperative protocol for orthopaedic cases). A modified Robert Jones bandage was placed on the affected limb in all dogs for the first 24–36 hours. Non-steroidal anti-inflammatory drugs together with tramadol in some cases were administered in the early postoperative period, generally seven to 14 days. Cephalexin (22 mg/kg orally every 8 hours) was also administered to all dogs for seven to 10 days postoperatively. After bandage removal, physical therapy was instituted to mobilize the joints. Dogs were discharged five to seven days after surgery with instructions to the owners for strict activity restriction for a minimum of eight weeks. Owners were instructed to continue the physical therapy, and all were encouraged to seek professional physical therapy assistance.

Follow-up

In-hospital re-evaluation and postoperative radiographic evaluation of healing was scheduled in all cases at eight to 12 weeks after surgery. If radiographic union was not complete, further follow-up and radiographic evaluation was obtained. During each in-hospital re-evaluation, limb function was subjectively assessed and any lameness graded as mild (weight bearing), moderate (weight bearing with occasional non-weight bearing), severe (predominantly non-weight bearing), or non-weight bearing. Any postoperative complications were recorded. Major complications were defined as those that required either further surgical or medical treatment to resolve; minor complications were those that were noted on physical examination but required no further surgical or medical treatment (20).

Further long-term follow-up was obtained through telephone interview at the time of data collection for this report using a 1–10 visual analog scale (VAS) scoring system (►Appendix III: available online at www.vcot-online.com) (21). Owners were

Table 1 Summary data for the femoral deformities, and the secondary tibial deformities.

Limb	Breed	Age (mo)	Sex	Weight (kg)	Side	aLDFA	MPTA	MDTA	Femoral angulation (gross estimate)
1[a]	Mix	15	FS	13.6	Right	66° *	92°	96°	34° valgus 26° recurvatum
2[a]	Mix	16	FS	13.8	Left	76° *†	N/A	N/A	24° valgus
3	Giant Schnauzer	11	FS	26.2	Left	57° *†	N/A	N/A	21° valgus 74° recurvatum
4	Dobermann Pinscher	50	MC	61.0	Left	56° *†	N/A	N/A	15° valgus (proximal) 33° valgus (distal) 23° recurvatum
5	Mix	9	MC	23.0	Right	71° †	N/A	N/A	26° valgus (proximal procurvatum & distal recurvatum)

[a] Indicates bilateral surgery (same letter designation indicates same dog). * Determined retrospectively. † Angles determined from stereolithography apparatus biomodels. MC = male castrated; FS = female spayed; aLDFA = anatomic lateral distal femoral angle; MPTA = medial proximal tibial angle; MDTA = medial distal tibial angle; N/A = not available; LPL = lateral patellar luxation.

Table 2 Summary data for the postoperative femoral (and tibial) deformity correction and fixation technique.

Limb	aLDFA	MPTA	MDTA	Osteotomy femur	Fixation femur	Comments
1[a]	90° *	93° *	N/A	FHO; MCWO & torsion correction	9-hole ALPS 8 (lateral), 7-hole ALPS 8 (medial) – compression (both plates)‡	FHO
2[a]	90° *	94° *	95° *	MCWO	10-hole ALPS 8 (lateral), 8-hole ALPS 8 (medial) – compression (both plates)‡	
3	92° *	91° *	90° *	CrOWO, LOWO & torsion correction	2 12-hole ALPS 10 (medial), 14-hole & 12-hole ALPS 10 (lateral), 3.5-mm cortical screw with plastic spiked washer (LDE); 6 ml fine mix allograft	Intra-operative correction of recurvatum limited to 52°; limited stifle & hock joint flexion
4	86° *	91° *	89° *	MCWO & torsion correction (proximal); CrOWO & LOWO (distal)	8-hole 3.5-mm LC-DCP (cranial) – compression‡ (proximal) 14-hole ALPS 11 & 9-hole ALPS 10 (lateral), 9-hole ALPS 11 & 8-hole ALPS 10 (medial); 6 ml fine mix allograft	Intra-operative correction of recurvatum limited to 13°; limited stifle & hock joint flexion
5	97°	92°	96°	Transverse osteotomy & torsion correction (proximal); MCWO & CaCWO (distal)	5-hole ALPS 10 (cranial) – compression‡ (proximal, 10-hole ALPS 10 (lateral), 8-hole ALPS 10 (medial) – compression (both plates)‡	Recurvatum and procurvatum not addressed

[a] Indicates bilateral surgery (same letter designation indicates same dog). *Determined retrospectively. *In all cases, exposure of the distal femur was obtained with a tibial tuberosity osteotomy (TTO), reflected proximally to expose the entire distal femur. † Sulcoplasty performed with rongeurs and smoothed with file (cartilage surface either found destroyed or uneven). ‡ Compression plate fixation by eccentrically loading 1–2 screws in plate hole(s). aLDFA = anatomic lateral distal femoral angle; ALPS = advanced locking plate system; CaCWO = caudal closing wedge osteotomy; CrOWO = cranial opening wedge osteotomy; FHO = femoral head and neck ostectomy; G = gauge; K-wires = Kirschner wires; LC-DCP = limited contact dynamic compression plate; LDE = long digital extensor tendon; LOWO = lateral opening wedge osteotomy; MCWO = medial closing wedge osteotomy; MDTA = medial distal tibial angle; MPTA = medial proximal tibial angle; N/A = not available; TB = tension-band wire; TTT = tibial tuberosity transposition; TWR = trochlear wedge recession.

Femoral torsion (gross estimate)	Tibial angulation (gross estimate)	Tibial torsion (gross estimate)	Other findings
18° external	Within normal limits	Within normal limits	Grade 4 LPL nonunion femoral neck
WNL	18° valgus	~40° external	Grade 4 LPL
21° external	4° valgus	~20° external	Patella baja
15° external (proximal)	Within normal limits	~25° external	Grade 4 LPL
18° external (proximal)	Within normal limits	~20° external	Grade 4 LPL

Joint procedures	Osteotomy tibia	Fixation tibia*
Sulcoplasty†		**TTO:** 1.6 mm & 1.14 mm K-wires, 18G TB
Sulcoplasty† TTT (~3 mm medial)	Closing wedge osteotomy & torsion correction	**TTO:** Two 1.6 mm & 1.14 mm K-wires, 18G TB; 13-hole ALPS 8 (medial), 12-hole ALPS 5 (cranial)
TWR TTT (~2 mm medial)	Closing wedge osteotomy & torsion correction	**TTO:** Three 1.6 mm K-wires, 18g TB; cranial 18G TB at osteotomy, 9-hole 3.5-mm LC-DCP – compression‡
TWR TTT (~3 mm medial)	Transverse 1 cm ostectomy & torsion correction	**TTO:** Three 1.6 mm K-wires, 16G TB; 12-hole 3.5 mm Broad LC-DCP – compression‡
TWR TTT (~3 mm lateral)	Transverse osteotomy & torsion correction	**TTO:** Two 1.6 mm K-wires, 16G TB; 10-hole 3.5 mm LC-DCP – compression‡

asked to evaluate their dog's lameness and ability to tolerate exercise, as well as their impression of the success of surgery performed, and whether or not they would have the surgery performed again under the same circumstances. Owners also were asked to report any further complications or any subsequent surgery performed on the affected limb after the original surgery.

Results

Bilateral distal femoral malunions were present in one dog, and unilateral malunions in the remainder. Mean body weight was 27.5 kg (range: 13.6 – 61.0 kg). Mean age at surgery was 20.2 months (range: 11 – 50 months). All dogs were ambulatory with varying degrees of lameness on the affected limbs, with moderate disuse muscle atrophy, and obvious angular limb deformity. Lameness was worse in all dogs after exercise and prolonged rest. Please see ►Table 1.

All dogs had significant distal femoral valgus, and distal femoral recurvatum and femoral torsion. Two dogs had biapical deformities, with additional proximal femoral angulation, torsion or both combined (limbs 4 and 5). These were corrected with a transverse or closing wedge osteotomy or a combination of both, and bridged with compression plate fixation[d,e] (limited contact-dynamic compression plate [LC-DCP], advanced locking plate system [ALPS]; limbs 4 and 5, respectively). All distal femoral deformities were corrected with either a closed or opening wedge osteotomy, together with rotational correction if required. In two dogs (limbs 1, 2, 5), a closing wedge osteotomy was performed and stabilized with bilateral (medial and lateral) ALPS hybrid[e,f] locking compression plate fixation (two total). In two dogs (limbs 3 and 4), femoral opening wedge osteotomies were performed so as to

d LC-DCP®: DePuy Synthes® Vet, West Chester, PA, USA

e ALPS: Kyon Pharma, Inc., Boston, MA, USA

f Hybrid locking plate fixation refers to a combination of standard and locking techniques in the same application, e.g., locking screw fixation in the short distal metaphyseal segment, but standard screw fixation, as in this instance, to compress the fracture to the diaphysis.

preserve limb length; in these cases, the opening wedge osteotomy was bridged with two bilateral (medial and lateral) ALPS locking bridging plates (four total). Please see ►Table 2.

Femoral length disparity between both sides was minimal (<5%) in the two dogs with the closing wedge osteotomies (limbs 1, 2, 5). In the two dogs with opening wedge osteotomies (limbs 3 and 4), there was considerable difference in the length of the respective femurs compared to the normal side preoperatively (estimated 25% and 29%, respectively). In both cases, the opening wedge osteotomies slightly improved the femoral length discrepancy observed postoperatively to approximately 16% and 21%, respectively. Postoperative aLDFA were within the target angles with a mean of 91° (range: 86–97°). Target aLDFA was 90° in limbs 1–4, and 97° in limb 5. Please see ►Table 2.

All dogs also had severe tibial torsion, two of which also had proximal tibial valgus, managed by transverse osteotomy, closing wedge osteotomy, or a combination of both, bridged with compression plate fixation. Please see ►Table 2.

All five dogs had stifle joint abnormalities: five had incomplete sulci, four had grade 4 lateral patellar luxation, and one had patella baja. Considerable joint dissection was required to debride the fibrous connective tissue and mobilize the patella in all dogs; furthermore, a trochleoplasty was necessary as all sulci were either under-developed or misshapen. A trochleoplasty of the femoral sulcus was performed in all dogs; additionally a tibial tuberosity transposition was performed to re-align the quadriceps mechanism in four limbs and to correct patella baja in the remaining limb. Please see ►Table 2.

Complications

In the dog with bilateral malunions (limbs 1 and 2), some restriction of the coxofemoral joint range of motion (ROM) was present as a result of the contracture associated with the long-standing right-sided femoral head and neck nonunion and treatment by femoral head and neck ostectomy (limb 1). Postoperative physical therapy resulted in near normal ROM (~160° extension).

In one dog (limb 3), the long digital extensor tendon was inadvertently transected at its origin; this tendon was re-attached to the femoral condyle with a 3.5 mm cortical bone screw and plastic spiked washer[g]. In addition, the recurvatum correction planned was determined to be excessive due to the inability to obtain sufficient stifle joint flexion; therefore, under-correction of the recurvatum was performed as a compromise. Stifle joint flexion postoperatively was limited to ~110°; however, postoperative physical therapy restored normal ROM (~50°). Limitation of tibiotarsal joint flexion (~135°) was also present due to gastrocnemius lengthening, also as a result of the recurvatum correction. Physical therapy was difficult; however, near normal function and ROM (~60°) was successfully obtained after considerable effort with professional rehabilitation. See also ►Table 3.

In another dog with a similar recurvatum correction (limb 4), recurvatum was again slightly under-corrected for identical reasons. Postoperatively, stifle joint flexion was initially ~130°; postoperative physical therapy successfully restored full ROM. During correction of tibial torsion, a 1 cm ostectomy of the tibia also was performed in an attempt to minimize gastrocnemius lengthening. Decreased tibiotarsal flexion postoperatively (initially ~120°) resolved quickly with physical therapy, and an almost full ROM was restored. A peroneal nerve neurapraxia was noted at the first re-evaluation at five weeks postoperatively, at which time the dog was observed to compensate by "flipping" the paw forward with advancement. This persisted (albeit improved) at nine weeks, and fully resolved sometime before the subsequent follow-up at 26 weeks postoperatively. An iatrogenic injury to the nerve was assumed to have occurred during the tibial osteotomy. Please see ►Table 3.

Table 3 Summary follow-up information on lameness, radiographic healing, and complications.

Limb	Lameness (in-hospital evaluation)	Radiographic Healing	Complications
1[a]	Moderate 5 weeks Moderate 11 weeks Mild 17 weeks Mild 57 weeks	IC 5 weeks C 11 weeks	None; mild lameness right hindlimb attributed to FHO
2[a]	Mild 6 weeks Mild 12 weeks Mild 52 weeks	IC 6 weeks C 12 weeks	None; mild lameness right hindlimb attributed to FHO
3	Moderate 5 weeks Moderate 9 weeks Mild 113 weeks	IC 5 weeks IC 9 weeks C 113 weeks	Cut origin to LDE; re-attached with screw & spiked washer intra-op. Unable to make full recurvatum correction due to soft-tissue limitation (limited stifle and hock joint flexion with full correction); persistent limited hock joint flexion – resolved with extensive physical therapy; mild persistent lameness
4	Moderate 5 weeks Mild 9 weeks Mild 26 weeks	IC 5 weeks IC 9 weeks C 26 weeks	Unable to make full recurvatum correction due to soft-tissue limitation (limited stifle and hock joint flexion with full correction); exaggerated pes advancement at both 5 & 9 weeks secondary to presumed iatrogenic peroneal nerve injury (neurapraxia); resolved by 26 weeks; mild persistent lameness
5	Mild 8 weeks None 24 weeks	C 8 weeks	None

[a] Indicates bilateral surgery (same letter designation indicates same dog). IC = incomplete; C = complete; FHO = femoral head and neck ostectomy; LDE = long digital extensor tendon; intra-op = intra-operatively.

g DePuy Synthes® Vet, West Chester, PA, USA

Two dogs required more extensive rehabilitation, and were thus considered as having major complications. A minor complication was noted for the dog with the peroneal nerve neurapraxia, which resolved with time and without any specific therapy.

In-hospital re-evaluation

All dogs were evaluated until documented complete osteotomy healing was observed radiographically. Radiographic healing occurred by a mean of 34 weeks (median: 12 weeks, range: 8–12 weeks for the closing osteotomies, and 26–113 weeks for the opening wedge osteotomies). Final in-hospital re-evaluation of limb function (ROM, signs of discomfort, lameness) was available for all dogs, and was performed at a mean of 54.4 weeks postoperatively (range: 24–113 weeks). All dogs improved dramatically and all were functioning normally; however, only one dog was not lame (limb 5), while the remainder had a mild lameness at this time. Please see ►Table 3.

Long-term follow-up

Long-term follow-up evaluation (telephone) was obtained for all dogs at a mean of 28.6 months after surgery (range: 5-42 months). No additional complications or additional surgical procedures were reported for any dog. The VAS scores are summarized in ►Table 4. Only the right pelvic limb of the bilaterally affected dog (limb 1) had a lameness score less than 9, which was occasionally exacerbated with exercise. In four dogs, the owners were highly satisfied with the overall outcome from surgery. In one dog (Giant Schnauzer, limb 3), the owner was partially satisfied and uncertain if he would pursue surgery again. In this dog, limb function was remarkably good preoperatively, despite the lameness; however, on physical examination, signs of hip pain were present with radiographic evidence of femoral head and neck malalignment secondary to abnormal femoral alignment. Although this owner was concerned about the limb function at this time, he later (at the time of long-term telephone follow-up) retrospectively assessed the dog to be normal preoperatively (score of 10, re: never lame). This was the only dog graded less than 9.5 postoperatively in the latter two categories. It should be noted that at this time this dog was performing competitively in agility trials. Please see ►Table 4.

Table 4 Results of long-term follow-up evaluation with the owners via telephone interview (see ►Appendix 3: available online at www.vcot-online.com).

	Mean response	Range
Preoperative exercise tolerance	4.4	2–10
Postoperative exercise tolerance	8.7	6–9.5
Lameness when walking preoperatively	3.6	1–10
Lameness when walking postoperatively	8.7	6–9.5
Dog's current lameness score (time of telephone follow-up)	9.2	6–10*
How would you grade the success of the operation (for each limb)	8.7	5–10†
Operation done again in the same circumstances	8.2	2–10†

*Only limb 1 had a response <9; †Only limb 3 was evaluated <9.5.

Discussion

This report establishes a successful and repeatable method of repair for complex distal femoral malunions with good results using SLA biomodels for deformity evaluation and surgical planning, with multiple locking plate fixation. All deformities were easily evaluated using the 3D biomodels. Rehearsal surgery was performed in each, which identified all confounding bone issues before the definitive surgery was performed. These biomodels also were very useful as a visual representation of both the deformities and the planned corrections for owner education.

Repeating measurements obtained from the biomodels and transcribing them to the bone is one method used to transfer the plan to the bone; however, this is predicated on identification of the bone surface in either the frontal or sagittal planes, which can be difficult with multiplanar or torsional deformities when the entire bone is not visualized (3). Cutting guides (templates made directly from the model) is one method used to increase the accuracy associated with the translation of the rehearsal surgery to the patient and has also been previously reported in humans and in experimental studies in dogs (9, 22). Our method was to use guide wires, starting with the distal joint surface (as performed with the rehearsal surgery on the biomodels, and which was consistently identifiable intraoperatively) and moving sequentially to place additional wires to reproduce their preplanned positioning in the patient. These wires also served as the orientation lines for placing the osteotomies, as has been described in the dog and in humans (1, 23-25). The accuracy of this technique also has been documented experimentally in the dog (26).

A limitation of the 3D biomodels and the rehearsal surgery, however, is that any soft-tissue constraints cannot be identified preoperatively. This was evident in the two dogs, limbs 3 and 4, where full correction of the recurvatum would have resulted in unacceptable lengthening of the quadriceps and gastrocnemius mechanisms, resulting in decreased stifle and hock flexion.

In all cases, physical therapy was performed to maintain or improve ROM, as all were chronic conditions with altered joint ROM, and postoperative restriction was anticipated. There is no question of the importance of physical therapy in such cases, where chronic conditions contribute to the loss of the joint ROM and function, which is compounded by a surgical procedure that results in lengthening on the soft-tissues (27, 28).

Locking plate fixation was chosen for stabilization of the distal femoral corrective osteotomy just proximal to the femoral sulcus, and with an implant that allowed in-plane plate contouring to follow the femoral procurvatum. Furthermore, with the large gaps created in the two dogs with opening wedge osteotomies, bilateral double plate bridging fixation was considered to provide excellent stability while preserving the "biological footprint" compared to standard plates (which compromise the vascularity under the plate), as observed with uncomplicated healing of these osteotomies (29–31). Healing of the closing wedge osteotomies was comparable to that observed in uncomplicated fracture healing. Although the healing of the opening wedge osteotomies appeared to be prolonged, incomplete healing was observed at the expected early time frames postoperatively. There was a large delay until the final radiographic evaluations that documented complete healing; it is reasonable to assume that complete healing occurred much earlier in both of these dogs.

In all dogs, there was patellar malpositioning, all of which were a result of the femoral malalignment. We assumed that the stifle issues were the primary reason for the lameness observed; however, the altered joint forces probably also contributed. Femoral re-alignment essentially corrected the patellar malalignment in all dogs, with only slight modifications of the tibial tuberosity position performed to ensure appropriate quadriceps alignment.

Tibial corrections were performed in four out of five limbs. The primary nature of these deformities were torsional, which can reasonably be presumed to be compensatory as a result of altered weight bearing with uneven physeal pressures during growth (32, 33).

Final measurements of distal femoral and proximal tibial joint angles were within the normal range immediately postoperatively. As noted, our initial target aLDFA was 90° in four out of five limbs, as femoral and tibial alignment angles were yet to be published. We did not, however, perform a total pelvic limb alignment measurement or evaluation. This would have added additional objective information as to the completeness of the corrections obtained (34). We currently recommend obtaining 3D biomodels of the entire pelvic limbs.

Based upon owner assessment and response to a questionnaire, the results of the long-term follow-up in these cases were excellent. It is important to note that this assessment may be biased due to financial investment and its subjective nature. Improved muscle mass was reported in all dogs compared to the initial preoperative evaluations. These assessments also must be considered in light of the lack of any objective criteria. An objective evaluation with, for example, both pre- and postoperative force plate analysis would be required to more definitively and objectively determine the degree of improvement or the lack thereof.

All but one dog had a mild lameness at the end of the in-hospital evaluation period. This finding was not unexpected due to the severity of the deformities and the resultant shortened femoral length compared to the opposite femurs in all dogs. Also, in the one dog (limb 1) with the poorest owner assessment, we attributed the poorer function in this limb to hip joint discomfort as a result of the femoral head and neck osteotomy (35).

The long digital extensor tendon injury in one dog was avoidable, albeit difficult due to the nature of the fibrous connective tissue changes around the joint. No subsequent issues were identified post-repair after this intraoperative complication. The presumed peroneal nerve neurapraxia also was an avoidable iatrogenic injury during surgery.

The major problem encountered was the limited tibiotarsal joint flexion in two dogs as a result of the large recurvatum correction. Despite our definition that these were major complications, it could be reasonably argued that such limitation of ROM postoperatively, which required a concerted effort with postoperative physical therapy, could reasonably be expected due to the chronic nature of the deformities. In the second dog with this problem, it appeared that the tibial ostectomy ameliorated the restricted tibiotarsal joint flexion as a result of the femoral recurvatum correction. Additional experience would be required to confirm this assertion.

In the one dog in which the owner was less than satisfied (limb 3), and identified with hip pain as a result of femoral head and neck malalignment, the latter was corrected with return of appropriate femoral alignment and stifle joint conformation. We believe that without femoral correction, this dog's function would have progressively worsened; however, this is only supposition.

These complications illustrate the difficult nature of these complex deformity corrections. It is not our expectation to be able to return these dogs to normal function. Nevertheless, satisfactory clinical function can be gained, despite persistence of a mild lameness. It also must be noted that the disparity in limb length did not appear to adversely affect these dogs' function, where a reduction of 10–20% of femoral bone length has been demonstrated experimentally to be tolerated in dogs by a compensatory increase in standing angle on the ipsilateral limb and the accommodating decrease in the angle of the stifle in the contralateral limb (36). The latter also has been observed and previously reported clinically (37). Regardless, the differences in limb length could account for any lameness found at the time of the final in-hospital evaluations and reported by the owners long-term. For this degree of shortening, limb lengthening with the correction could be an alternative; although, this would require alternative fixation methods to perform distraction (e.g., external skeletal fixator). Regardless, there also remains a limitation as a result of the soft tissues (pain, nerve palsy, muscle contraction), even with distraction osteogenesis (38).

Re-alignment of the quadriceps mechanism to address the patellar abnormalities in all of these dogs probably resulted in the majority of the clinical improvement observed, this despite any persistent limb length discrepancy. We presume that the severity of any future issues (e.g., osteoarthritis and subluxation) as a result of the original malalignment also were ameliorated; however, this is only an assumption, as long-term follow-up and re-evaluation of the stifle and adjacent joints have not been critically evaluated.

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Conflict of interest

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