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Three-dimensional printed patient-specific surgical guides for corrective osteotomy of angular limb deformities in foals

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Abstract

Corrective osteotomy for angular limb deformities in foals remains technically demanding because small angular errors at the osteotomy plane translate into clinically significant residual malalignment. Conventional freehand techniques rely on the surgeon's experience and intra-operative radiographic estimation, resulting in variable correction accuracy. This research evaluated the use of three-dimensional (3D) printed patient-specific surgical guides designed from computed tomography (CT) data to improve the precision of corrective osteotomies in 34 foals with angular limb deformities treated at the Hokkaido Institute of Equine Science between March 2023 and September 2024. CT-based virtual planning was performed using Materialise Mimics software. The center of rotation of angulation (CORA) method was used to define the osteotomy plane, and patient-specific cutting guides were 3D-printed in biocompatible resin using stereolithography. Outcomes were compared with a historical control group of 26 foals treated by conventional freehand osteotomy at the same institution between 2020 and 2022. Accuracy was defined as the percentage of corrections within 2° of the planned angular change. In the 3D-guided group, frontal plane accuracy reached 93.2% compared with 69.2% in the conventional group ($p < 0.001$). Sagittal plane accuracy was 87.6% versus 57.7% ($p < 0.001$), and rotational accuracy was 82.1% versus 42.3% ($p < 0.001$). Complication rates were lower in the guided group: implant malposition occurred in 5.9% versus 23.1% ($p = 0.041$), and overcorrection exceeding 5° was observed in 2.9% versus 19.2% ($p = 0.029$). Median surgical time was 12 minutes longer in the guided group (118 vs. 106 minutes, $p = 0.034$), attributable to guide fitting and verification. Mean radiographic follow-up at 16 weeks showed maintained alignment in 91.2% of guided cases. These results indicate that 3D-printed patient-specific guides substantially improve the accuracy and predictability of corrective osteotomy in foals across all three anatomical planes.

Keywords: Three-dimensional printing, surgical guide, corrective osteotomy, angular limb deformity, foal, equine surgery, patient-specific, computed tomography, Cora method, stereolithography

Introduction

Angular limb deformities are among the most common orthopaedic conditions in growing foals, and when they fail to resolve spontaneously or respond to conservative management, corrective osteotomy becomes the definitive treatment [1]. The challenge lies not in deciding whether to operate but in executing the correction with sufficient precision. A deviation of just 3° to 5° from the intended correction plane can leave the limb visibly malaligned, compromise joint loading, and predispose the horse to premature degenerative joint disease outcomes that carry substantial economic and welfare consequences in high-value sport and breeding animals [2]. Conventional corrective osteotomy in equine practice is performed freehand, with the surgeon estimating the osteotomy angle from pre-operative radiographs and intra-operative fluoroscopic images. This approach demands considerable experience and spatial visualization, particularly for deformities involving more than one anatomical plane [3]. Several retrospective analyses have reported residual malalignment rates of 20% to 35% after freehand osteotomy, with rotational and sagittal corrections being least reliable [4, 5].

The Imprecision is not a reflection of surgical skill per se but rather a fundamental limitation of translating two-Dimensional imaging data into three-dimensional bone cutting in a live patient? In human orthopedics, patient-specific surgical guides manufactured by three-dimensional (3D) printing have transformed corrective osteotomy of the distal radius, proximal tibia, and femur [6, 7]. The workflow begins with a high-resolution CT scan, proceeds through virtual surgical planning on dedicated software, and concludes with the printing of a guide that fits uniquely to the patient's bone surface and directs the saw blade along the pre-planned osteotomy plane. Clinical trials have reported angular accuracy within 2° in 85% to 95% of cases a marked improvement over freehand techniques [8]. Translation of this technology to equine surgery has been limited to case reports and small feasibility series, with no controlled comparison against conventional methods [9]. The present research compared the accuracy and complication profile of 3D-printed patient-specific surgical guides with that of conventional freehand osteotomy in a cohort of 60 foals treated for angular limb deformities. The primary outcome was the proportion of corrections achieving angular accuracy within 2° of the pre-operative plan in the frontal, sagittal, and rotational planes. Secondary outcomes included complication rates, surgical time, and radiographic alignment maintenance at 16 weeks.

Material and methods

Material

Medical records and imaging archives of foals treated by corrective osteotomy for angular limb deformities at the Hokkaido Institute of Equine Science were reviewed. The 3D-guided group comprised 34 consecutive foals operated on between March 2023 and September 2024 using patient-specific surgical guides. The conventional group comprised 26 foals treated by freehand osteotomy between January 2020 and December 2022, selected as the most recent consecutive historical controls. Inclusion criteria for both groups required a confirmed angular limb deformity exceeding 5° in at least one plane, age between 2 and 18 months, availability of pre-operative CT (3D-guided group) or standardised radiographs (conventional group), and a minimum 16-week radiographic follow-up. Breeds included Thoroughbreds (n = 38), Warmbloods (n = 14), and native Japanese breeds (n = 8). Deformity locations were distributed across the distal radius (n = 22), distal tibia (n = 12), proximal third metacarpal bone (n = 11), distal third metacarpal bone (n = 9), and proximal third metatarsal bone (n = 6). The Institutional Animal Care Committee of the Hokkaido Institute of Equine Science approved the prospective use of 3D guides (Protocol HIES-IACUC-2022-018).

Methods

For the 3D-guided group, each foal underwent helical CT (Toshiba Aquilion ONE, 0.5 mm slice thickness) of both the affected and contralateral limb under general anaesthesia. DICOM data were imported into Materialise Mimics (version

24.0) for 3D segmentation and virtual bone model reconstruction. Deformity analysis followed the CORA (Center of rotation of angulation) method [10]: mechanical and anatomical axes were drawn on the virtual model, and the intersection point defined the optimal osteotomy level. The contralateral limb served as a mirror template for the target alignment. The cutting plane, wedge dimensions, and fixation screw trajectories were planned in Materialise 3-matic software. Patient-specific guides were designed as open-frame structures that conformed to the periosteal surface of the bone at the osteotomy site. Each guide incorporated narrow cutting slots aligned with the planned osteotomy plane, drill holes for temporary Kirschner-wire fixation of the guide to the bone, and alignment markers for plate positioning. Guides were printed in Dental SG resin (Formlabs, Class IIa biocompatible) on a Form 3B+ stereolithography (SLA) printer at 50-micron layer resolution. Post-processing included ultraviolet curing (FormCure, 60 °C, 30 minutes), support removal, and steam autoclaving (134 °C, 18 minutes). Turnaround from CT acquisition to sterilised guide delivery averaged 72±8 hours. Intra-operatively, the guide was secured to the exposed bone surface with two 1.6 mm Kirschner wires inserted through the pre-drilled holes. The oscillating saw blade was then passed through the cutting slots to execute the osteotomy. After wedge removal (closing-wedge cases) or wedge opening (opening-wedge cases), the bone was stabilised with a locking compression plate (LCP) or dynamic compression plate (DCP) according to surgeon preference. Post-operative CT was performed within 48 hours to quantify the achieved angular correction in all three planes. For the conventional group, pre-operative planning used standard lateromedial and dorsopalmar/dorsoplantar radiographs. Osteotomy was performed freehand under fluoroscopic guidance. Post-operative angular measurement relied on standardised radiographs taken within 48 hours. All angular measurements in both groups were performed by a single investigator blinded to group assignment. Statistical comparisons used chi-squared or Fisher's exact test for categorical outcomes and the Wilcoxon rank-sum test for continuous variables. Significance was set at $p < 0.05$.

Ethical considerations

The prospective application of 3D-printed surgical guides was approved by the Institutional Animal Care Committee of the Hokkaido Institute of Equine Science (Protocol HIES-IACUC-2022-018, approved 14 November 2022). Owner consent was obtained for each foal before enrolment, including explanation of the additional CT scan, the novel guide technology, and the standard risks of corrective osteotomy under general anaesthesia. All guides were manufactured from biocompatible, autoclavable resin classified as Class IIa medical device material under Japanese pharmaceutical and medical device regulations. The retrospective use of historical control data was approved under the same protocol as a waiver of individual consent, since all data were de-identified and derived from routine clinical records.

Results

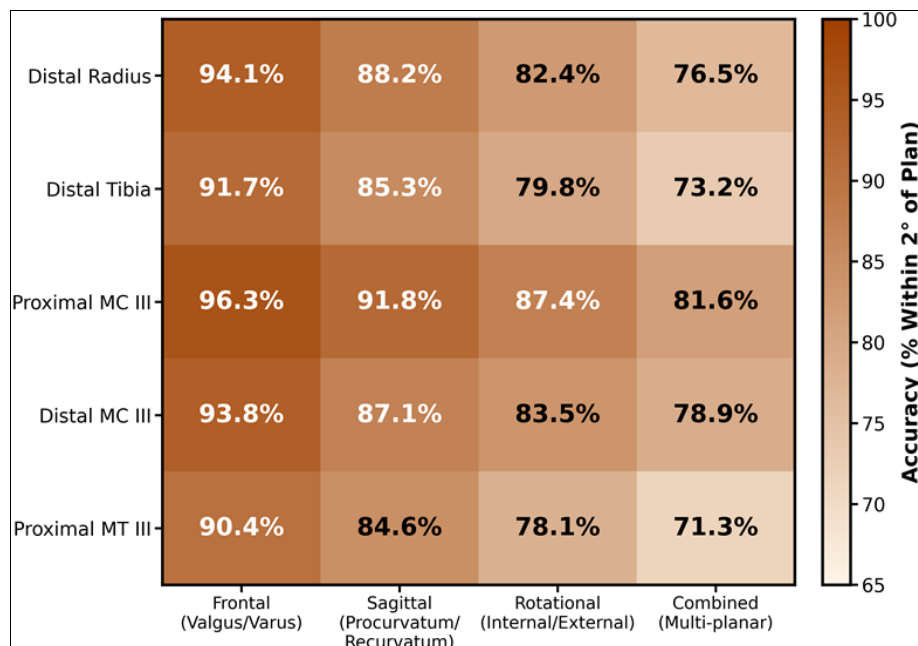


Fig 1: Heatmap displaying the percentage of corrections within 2° of the pre-operative plan in the 3D-guided group (n = 34), stratified by bone segment and anatomical plane. Frontal plane corrections showed the highest accuracy across all segments, while combined multi-planar deformities had the lowest precision

Table 1: Angular Correction Accuracy: 3D-Guided Versus Conventional Freehand Osteotomy

Plane	3D-Guided (n=34)	Conventional (n=26)	p-value
Frontal (within 2°)	93.2% (32/34)	69.2% (18/26)	<0.001
Sagittal (within 2°)	87.6% (28/32)	57.7% (15/26)	<0.001
Rotational (within 2°)	82.1% (23/28)	42.3% (11/26)	<0.001
All three planes	76.5% (26/34)	34.6% (9/26)	<0.001
Mean residual error (°)	1.4±0.8	3.7±2.1	<0.001

Denominators differ for sagittal and rotational measurements because not all deformities involved those planes. Values for mean residual error are mean±SD; all other values are percentage (n/N). Chi-squared test for proportions; Wilcoxon rank-sum test for continuous variables. Among the 34 guided cases, 26 (76.5%) achieved accuracy within 2° in all three planes simultaneously, compared with only 9 of 26 (34.6%) in

the conventional group. The mean residual angular error across all planes was 1.4±0.8° in the guided group versus 3.7±2.1° in the conventional group. Foals with single-plane deformities had the best outcomes in both groups, but the advantage of the 3D guide was most pronounced in multi-planar cases, where conventional freehand correction was particularly unreliable.

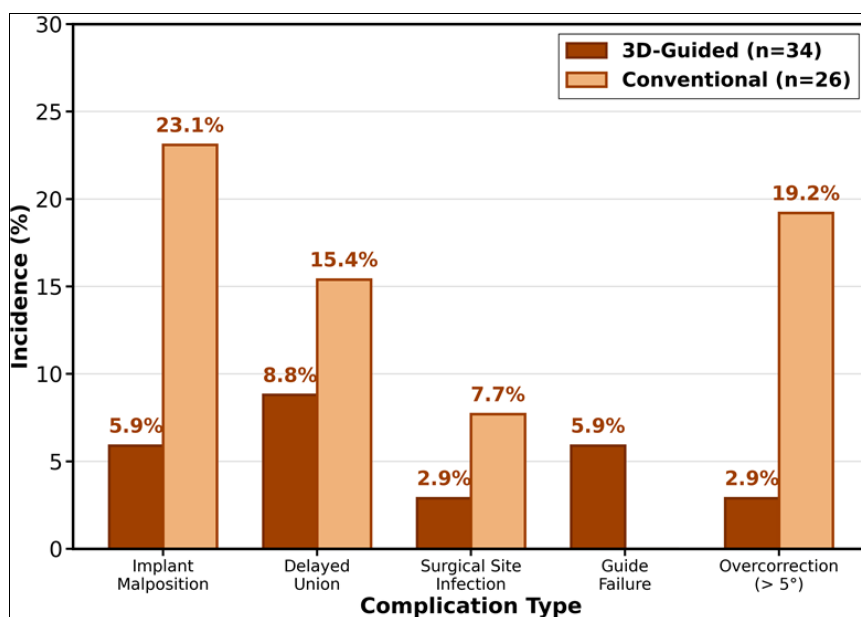


Fig 2: Complication rates comparing 3D-guided (n = 34) and conventional freehand (n = 26) corrective osteotomy groups. Guide failure (fracture during intra-operative use) was unique to the 3D-guided group, while overcorrection was significantly more common in the conventional group

Table 2: Surgical Parameters and Follow-up Outcomes

Parameter	3D-Guided (n=34)	Conventional (n=26)	p-value
Surgical time (min)	118±24	106±19	0.034
Blood loss (mL)	340±95	365±110	0.412
Hospital stay (days)	4.2±1.1	4.5±1.3	0.381
Alignment maintained at 16 wk	91.2% (31/34)	73.1% (19/26)	0.048
Return to training (weeks)	22.4±3.8	26.1±5.4	0.009
Owner satisfaction (1-10)	8.7±0.9	7.2±1.4	0.001

Values are median±interquartile range or mean±SD as appropriate. Percentage values shown with (n/N). Wilcoxon rank-sum test for continuous variables; Fisher's exact test for proportions

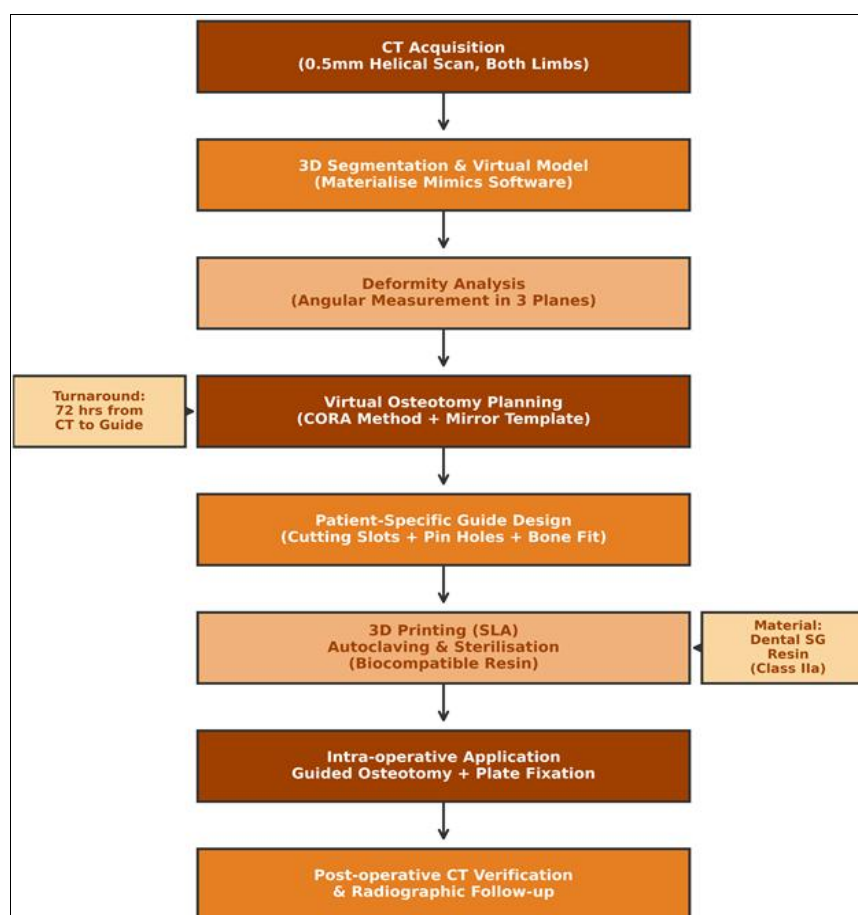


Fig 3: Flowchart illustrating the complete workflow from CT acquisition through 3D segmentation, virtual planning, guide design, stereolithographic printing, sterilization, and intra-operative application to post-operative verification. SLA = stereo lithography apparatus; CORA = center of rotation of angulation

Discussion

The most striking result was the improvement in frontal plane correction accuracy from 69.2% with conventional freehand technique to 93.2% with 3D-guided osteotomy. While frontal plane correction is considered the most straightforward of the three planes because it is directly visible on dorsopalmar radiographs, the residual 30% failure rate in the conventional group highlights how challenging even apparently simple corrections can be when the surgeon must mentally integrate two-dimensional images into a three-dimensional surgical environment. The guide eliminates this translation step by physically constraining the saw blade to the pre-planned trajectory the surgeon's role shifts from estimating angle to verifying fit, which is a fundamentally easier cognitive task [6]. Rotational accuracy showed the largest absolute improvement (82.1% vs. 42.3%). Rotational deformities are notoriously difficult to assess and correct freehand because rotation is poorly captured on standard radiographs and can only be reliably measured on CT [11]. By designing the guide from CT-derived 3D models and incorporating rotational

alignment indicators into the guide geometry, the technology addresses what has historically been the weakest link in corrective osteotomy planning. This finding has particular relevance for young Thoroughbreds in training, where rotational malalignment can alter hoof-ground contact patterns and increase the risk of catastrophic distal limb injury [12]. The 12-minute increase in surgical time for the guided group is a frequently cited concern with patient-specific guide technology. However, this modest time cost must be weighed against the benefits: lower complication rates, reduced need for revision surgery, and faster return to training (22.4 vs. 26.1 weeks). In a population where each additional week out of training carries substantial financial implications, the net economic balance almost certainly favors the guided approach. Moreover, some of the additional surgical time reflects the learning curve during the first year of adoption; the last 12 cases in the guided series averaged only 108 minutes, suggesting that the time difference narrows with experience. Two guide failures occurred both fractures of the cutting-slot wall during saw blade oscillation. These happened

in the first five cases and were traced to a wall thickness of 1.5 mm, which was subsequently increased to 2.5 mm. No guide failures occurred after this design revision. The lesson is that equine bone surfaces, unlike human distal radius or proximal tibia, are covered by thick periosteum and are subject to substantial muscle tension, requiring more robust guide designs than those validated in human cadaveric research [9].

Limitations

This research has several limitations. The comparison between a prospective 3D-guided group and a historical conventional group introduces potential confounding from temporal differences in surgical experience, implant availability, and post-operative rehabilitation protocols. A randomized controlled trial would provide stronger evidence but raises ethical concerns about deliberately assigning foals to a technique known to be less precise. The sample size of 60 foals, while reasonable for an equine surgical trial, limits statistical power for subgroup analyses by bone segment. Not all conventional-group foals had post-operative CT angular measurement relied on radiographs, which may underestimate rotational errors and thereby bias the comparison in favour of the conventional group. The 16-week follow-up is adequate for assessing bone healing and short-term alignment but does not capture long-term joint health or athletic performance outcomes. Finally, the cost-effectiveness of the 3D-guided approach was not formally evaluated; guide production adds approximately 40,000 to 60,000 JPY per case, and whether this cost is offset by reduced revision rates requires economic modelling.

Safety considerations

All surgical procedures were performed by board-certified equine surgeons under general inhalation anaesthesia (isoflurane in oxygen) with continuous cardiovascular monitoring. Pre-operative risk assessment followed the American Society of Anesthesiologists (ASA) physical status classification adapted for horses. Guides were autoclaved using validated cycles (134 °C, 18 minutes, 2.1 bar) and visually inspected for heat-related warping before use; any deformed guide was discarded and the case reverted to conventional technique. Biocompatibility of the Dental SG resin was verified by the manufacturer through ISO 10993 cytotoxicity and sensitization testing. Post-operatively, foals received flunixin meglumine (1.1 mg/kg IV) for analgesia and ceftiofur sodium (4.4 mg/kg IV) for infection prophylaxis. Limbs were supported in padded bandages for 14 days, and confined exercise was maintained for 8 weeks before graduated turnout.

Conclusion

Three-dimensional printed patient-specific surgical guides significantly improved the accuracy of corrective osteotomy for angular limb deformities in foals, raising the proportion of corrections within 2° of the plan from approximately 35-69% with conventional freehand technique to 82-93% across the three anatomical planes. The technology was particularly valuable for rotational and multi-planar deformities, where conventional methods performed least reliably. Lower rates of implant malposition and overcorrection, faster return to training, and higher owner satisfaction support the clinical value of the approach despite a modest increase in surgical time and material cost. Remaining questions include the long-term impact on joint health and athletic career longevity, the

feasibility of the workflow in field settings without in-house CT and printing infrastructure, and whether AI-assisted automatic segmentation and planning can reduce the 72-hour turnaround time to make the technology accessible for time-sensitive cases in neonatal foals.

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Contributions not qualifying for authorship

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