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Femoral Stem Placement for Total Hip Arthroplasty Using Three-Dimensional Custom Surgical Guides in Dogs: A Cadaveric Study

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Abstract

Objective The aim of this study was to assess the feasibility and accuracy of femoral stem placement for total hip arthroplasty (THA) using three-dimensional (3D)-printed custom surgical guides (CSGs).

Study Design Computed tomography (CT) scans of 7 cadaveric adult medium-sized (23.2–30.0 kg) dog femurs were acquired. A virtual plan was made using 3D models, and CSGs were designed to aid in optimal femoral stem positioning. Two surgeons with limited experience in THA performed stem implantation with CSGs for each limb. Following stem implantation, CT scans were repeated, and final stem alignment was measured and then compared with the preoperative virtual plan.

Results The median difference between planned and postoperative stem alignment with CSGs was –6.2 degrees (interquartile [IQR] –15.2 to 2.1 degrees) for stem version, 2.3 degrees (IQR –0.6 to 3.9 degrees) for varus/valgus angulation, and 1.8 degrees (IQR –0.1 to 2.9 degrees) for cranial/caudal stem angulation. The median difference in stem depth was 1.5 mm (IQR –1.2 to 3.1). Mean surgical procedure time for CSG surgeries was 44.1 $\pm$ 20.5 minutes for femoral stem implantation.

Conclusion The use of CSGs resulted in successful femoral stem placement by two novice THA surgeons. Novice THA surgeons may benefit from CSGs in the learning stages of THA, but further investigation is recommended prior to clinical implementation.

Keywords
- total hip arthroplasty
- total hip replacement
- total joint replacement
- 3D-printed guides
- dog

Introduction

Total hip arthroplasty (THA) is a well-accepted treatment option for a variety of hip disorders in dogs.[1] While the overall success rates range from 80 to 98% and can lead to excellent surgical outcomes, major complications requiring additional surgery are common.[2–4] Many of these complications are related to imprecise execution of the procedure, particularly for the femoral component (stem).[5] Accurate stem orientation and the level of the femoral head ostectomy (FHO) are important factors for the reduction of complication rates,[3] as poor stem alignment can increase the risk of intraoperative complications such as fissuring or fracture, or placement of an undersized stem predisposing to subsidence with subsequent luxation or fissuring/fracture.[1–6]

Surgical proficiency in THA in dogs is associated with a steep learning curve.[7,8] Consequently, inexperienced surgeons or low-volume surgeons have an increased chance of encountering complications. Interestingly, evidence that reduction in complication rates may not be directly correlated to increasing individual surgeon's experience has also been published.[9] Furthermore, the known challenges associated

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with press-fit THA have led to the implementation of adaptations such as prophylactic cerclage and/or plating, use of hybrid components, as well as proprietary system adaptations such as collars and interlocking lateral bolts to minimize the incidence of some common complications.[10,11]

The role of computer-assisted design (CAD) software in surgical planning, surgeon training, custom surgical guide (CSG) development, and robotic-assisted surgery is quickly expanding in human arthroplasty.[12–15] CSGs have been used in veterinary medicine and have showed improved surgical accuracy in a wide variety of applications,[16–20] but to our knowledge, no study has assessed virtual arthroplasty planning or CSGs for THA in dogs.

The purpose of this cadaveric study was to determine whether CAD software could be used for virtual femoral stem templating and to assess the feasibility and accuracy of three-dimensional (3D) CSGs for stem placement by inexperienced THA surgeons in cadaveric dogs. We hypothesized that CAD software could be used to successfully plan femoral stem size, that stem alignment would be within acceptable ranges.[5]

Materials and Methods

Preoperative Planning

Seven medium to large mixed breed dogs that were euthanized for reasons unrelated to the study were used. This study was approved by the institutional animal care and use committee (#201910714). Following euthanasia, Computed tomographic (CT) scans of the pelvis and hindlimbs were acquired, dogs were then kept fresh in a cooler at 4°C following imaging prior to surgery during CSG development. Digital Imaging and Communications in Medicine (DICOM) files were segmented, volume rendered, and exported as stereolithography files to the CAD software (3-Matic, Materialize N. V., Leuven, Belgium) for virtual planning. In addition, concurrent 3D models of press-fit cementless femoral stems (BFX, Biomedtrix, Boston, Massachusetts, United States) were available for templating using the same software. A modified femoral stem virtual plan using CAD software was executed following current published guidelines.[21] Once the virtual surgical plan was determined satisfactory by an experienced THA surgeon (Stanley Kim) (►**Fig. 1**), the virtual ostectomy and virtual femoral broaching guides were designed.

Virtual Guide Design and Printing

The ostectomy guide was created with features that would help ensure secure attachment to the femur and precise ostectomy location (►**Fig. 2**). The broaching guide was designed to assist in canal preparation starting with initial entry point drilling of the trochanteric fossa, reaming, broaching, and final stem placement (►**Fig. 3**).

All components were fabricated in ABS-M30i (Stratasys, Eden Prairie, Minnesota, United States) using a Fortus 450MC printer (Stratasys) using a biocompatible, production-grade thermoplastic (ABS M30i, Stratasys Inc).

Surgical Procedure

The surgical procedures were performed by a first-year small animal surgery resident (Jose Carvajal) and a board-certified surgeon (Daniel Lewis). Neither individual had previous experience as a primary surgeon with cementless THA. Each surgeon operated on femurs for each dog at random using the CSGs thereby modifying the traditional technique as previously described.[21] Surgical assistance was provided by one

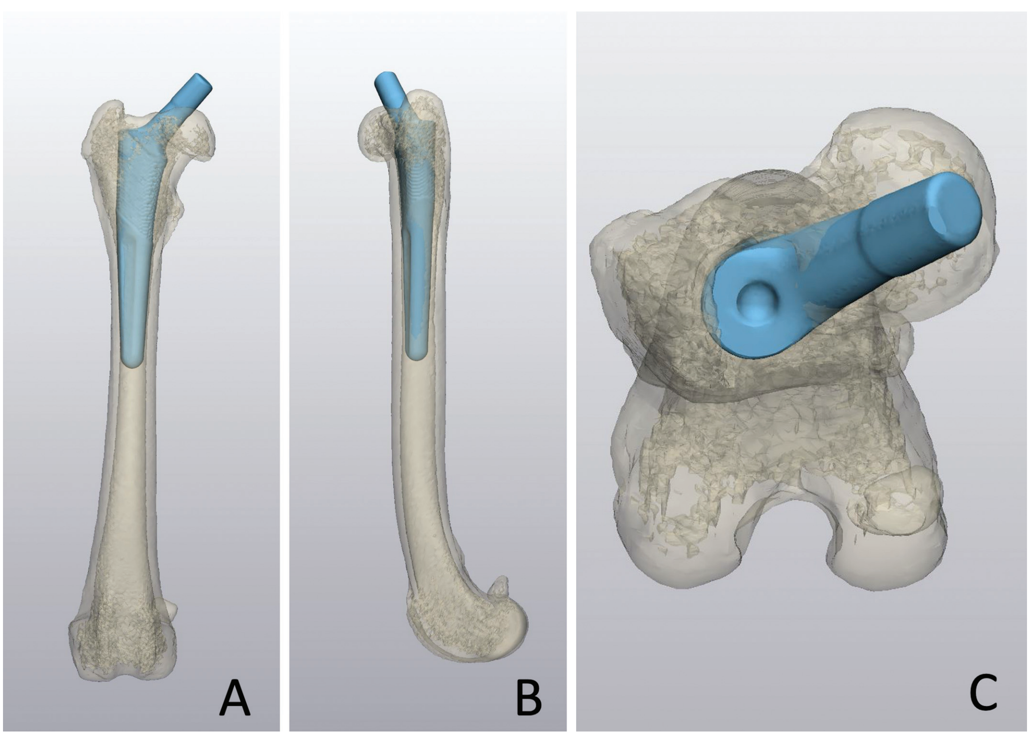

Fig. 1 Virtual plan. Modified virtual templating plan using three-dimensional rendered models of cadaveric femur and press-fit femoral stem in the coronal (**A**), sagittal (**B**), and axial (**C**) plane.

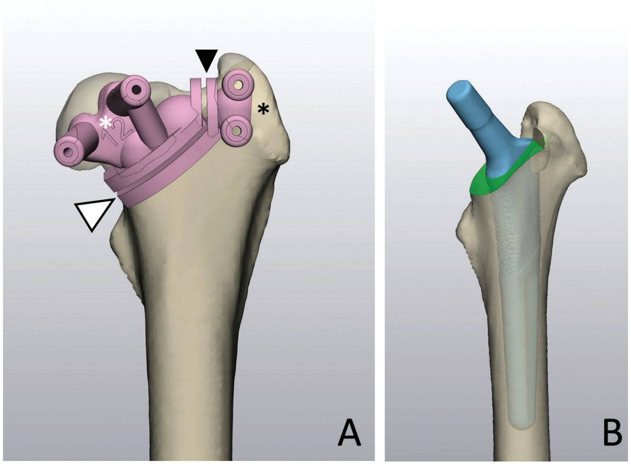

Fig. 2 Virtual ostectomy guide and plan. The guide was contoured to the femoral head and neck and designed to be secured into place with two converging Kirschner wire (k-wire) slots (adjacent to white asterisk), and two parallel trochanteric slots for added stability (adjacent to black asterisk). The cutting shelf has a 1-mm slot at an equivalent plane to the preplanned ostectomy (white arrowhead), with an "trochanteric overhang" cutting shelf when indicated (black arrowhead). (**B**) The ostectomy plane (green) is flush to the shoulder of the press-fit stem (blue) ensuring adequate room between the stem and cortical bone in the craniomedial plane.

veterinary student (Sarah Timko) who had no prior experience with THA, and a small animal surgeon (Hae Lee) who had significant experience with Zurich Cementless THA system (Kyon Veterinary Surgical Products, Boston, Massachusetts, United States). For each procedure, dogs were placed in lateral recumbency, the surgical leg was clipped with a number 40 blade and draped, and a routine craniolateral approach to the hip was performed.[21] Craniocaudal and lateromedial views of the 3D digital bone model and virtually implanted stem (including size of the stem) were available to the surgeon intraoperatively. The pelvic muscularity of each cadaveric dog was determined on a scale from 1 (severe atrophy), 2 (mild atrophy), 3 (normal), to 4 (very muscular).

For the modified CSGs procedures, the ostectomy guide was placed on the cranioproximal femoral head and neck. A partial "take-down" of the vastus lateralis along the cranial aspect of the greater trochanter was performed to allow proper placement of the CSGs. The guide's fit was confirmed to be flush with the femoral head and neck at the proximal, distal, medial, and lateral aspects of the guide and was secured into place with Kirschner wires. The ostectomy was created by keeping the saw blade in contact with the cutting shelf (►**Fig. 4A**). Once completed, the two trochanteric Kirschner wires were left *in situ* for placement of the broaching guide. The broaching guide was placed over the trochanteric Kirschner wires and secured in place with an additional trochanteric post. Proper fit was confirmed when the guide's safety shelf sat flush with the osteotomy surface. After initial drilling with a 5-mm drill bit, the drill post was cut and removed for subsequent reaming and broaching. The femoral broach was aligned by the surgeon using the broaching guide's alignment posts as a reference in the coronal, sagittal, and axial planes (►**Fig. 4B**). Placement of both guides was subjectively graded by each surgeon as easy, moderate, or difficult. Procedural advice during the ostectomy, reaming, or broaching by either assistant during CSGs procedures was not permitted. Final stem size was planned

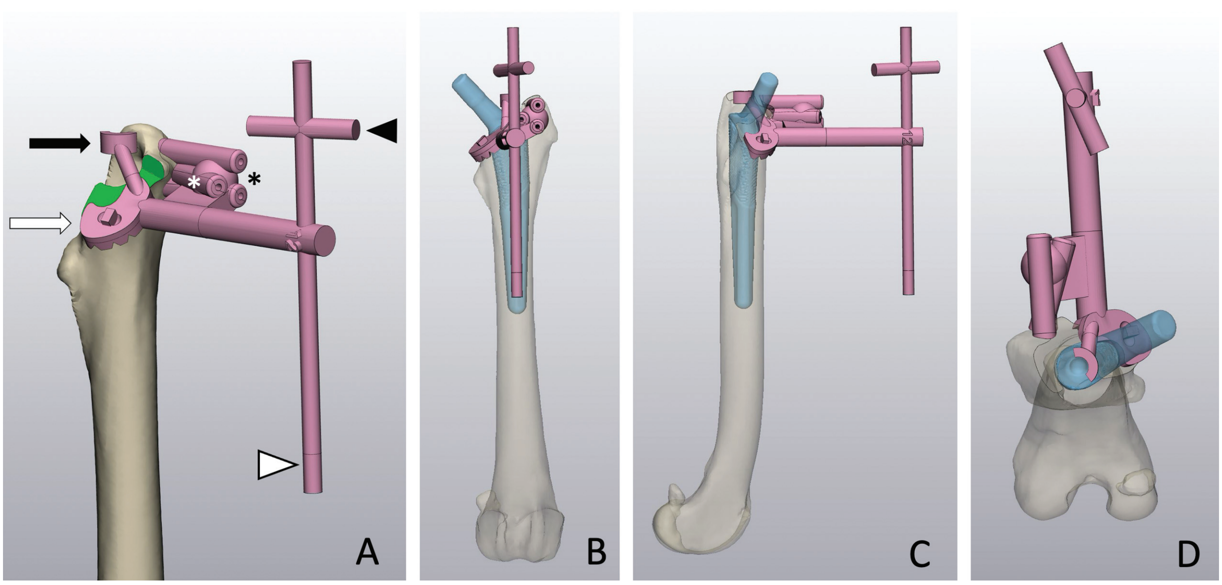

Fig. 3 Virtual femoral broaching guide. (**A**) The guide is contoured to the calcar region following ostectomy of the femoral head and neck. It features the same two parallel trochanteric posts (adjacent to black asterisk) in (Fig. 2A) with a single converging post (white asterisk) for added stability. A drill post was designed for guiding of the initial entry point into the trochanteric fossa (black arrow), an aiming post intended to provide the surgeon with the ideal sagittal and coronal stem axiality (white arrowhead), a shorter "version" shaft positioned on the aiming post (black arrowhead), and a broaching "safety shelf" (white arrow) resting on the ostectomy surface (green) with a crescent-shaped component corresponding to the ideal central position of the terminal broach and stem. (**B**) The aiming post is coaxial to the stem (blue) in the coronal plane. (**C**) The aiming post is coaxial to the stem in the sagittal plane. (**D**) The version shaft is 90 degrees to the stem orientation in the axial plane, and the drill post marks the ideal drilling location based on the center of the stem.

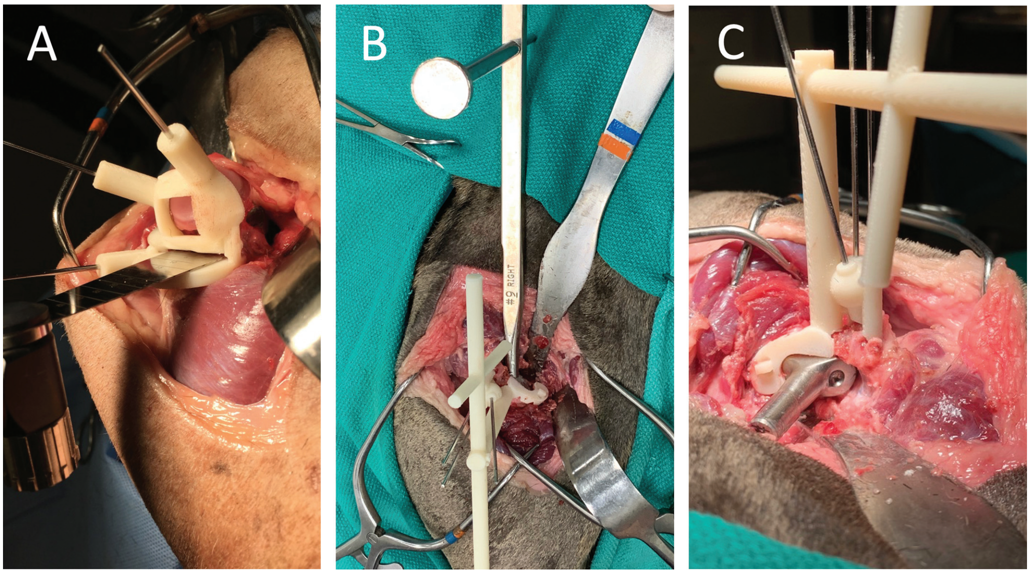

Fig. 4 Intraoperative images. (**A**) The sagittal saw blade is sitting flush to the cutting shelf while performing the ostectomy. (**B**) The femoral broach is coaxial to the aiming post, and the version shaft is coaxial to the cemented stem impactor. (**C**) Final stem implantation with the femoral broaching guide on. Note the drill post is removed following initial drilling.

based on preoperative template or when contact was made between broach and medial aspect of the safety shelf (►**Fig. 4C**). After the stem placement was completed, the femur was dissected from the surrounding tissue for postoperative CT imaging.

The time was recorded for each component of the procedures including: the approach (skin incision to the exposure of the femoral head and neck), guide placement (placement of the guides on the femur until they were secured with Kirschner wires), the ostectomy, canal preparation (initial drilling to terminal broaching), and stem placement (stem placement until press-fit is achieved).

CT Analysis and Data Collection

CT scans of the femurs with implanted stems were acquired, and the DICOM images were exported to the CAD software 3-Matic. The postoperative CT images were measured and compared with the preoperative plan by superimposing the pre- and postoperative femurs using a translational function and calculating the degree of difference between the two implants in the *x*, *y*, and *z* planes (►**Fig. 5**). The variables assessed included stem angulation in the coronal ($Stem_{cor}$) plane with negative values indicating varus, in the sagittal ($Stem_{sag}$) plane with negative values indicating cranial angulation, and in the axial ($Stem_{ax}$) plane with negative values indicating normo-version or retro-version ($>$ 15 degrees). Additionally, stem depth and the Hausdorff distance (HD), which is defined as the degree of mismatch between two data sets, were used to assess the degree of positioning error between the preoperative and postoperative models.

Statistics

For continuous numeric data, normality was evaluated using the Shapiro–Wilk test. Continuous, numeric nonparametric data sets were summarized as median and range. Differences between surgeons were not investigated.

Results

Surgical Procedure

Seven BFX femoral stem implants were placed in seven medium to large mix breed cadavers, with average bodyweight of 25.6 kg ($\pm$3.6). Five stems of the correct size were inserted, while two were undersized compared with preoperative planning. Results of individual dog's muscularity, difficulty of guide placement, total surgical time (minutes), maximum HD, virtual stem size, and final stem size are listed in ►**Table 1**. Mean surgical procedure time for CSG surgeries was 44.1 $\pm$ 20.5 minutes.

CT Analysis

Results for stem alignment are available in ►**Fig. 6**. The median difference between planned and postoperative stem alignment with CSGs was –6.2 degrees (interquartile [IQR] –15.2 to 2.1 degrees) for stem version, 2.3 degrees (IQR –0.6 to 3.9 degrees) for varus/valgus angulation, and 1.8 degrees (IQR –0.1 to 2.9 degrees) for cranial/caudal stem angulation. The median difference in stem depth was 1.5 mm (IQR –1.2 to 3.1). The mean HD difference was 0.68.

Discussion

The implementation of a virtual plan and use of CSGs was feasible for femoral stem implantation in all cadavers. Further investigation should be considered for the use of CSGs as they may be useful for inexperienced THA surgeons. The final stem position was acceptable in all cases, and no major intraoperative complications occurred during the femoral preparation process.

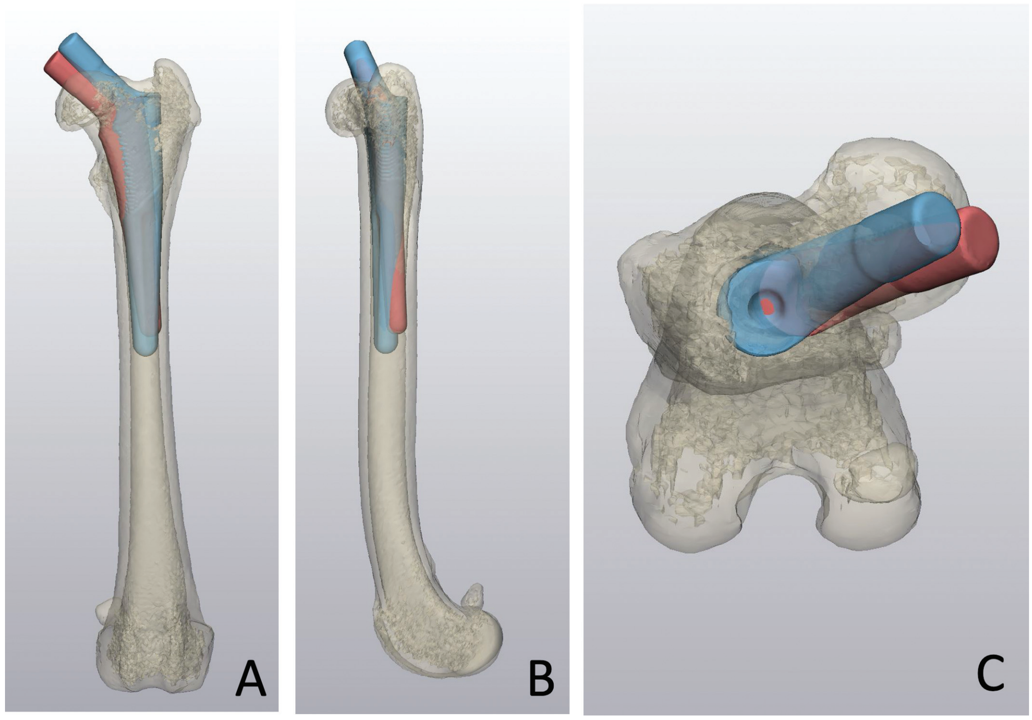

Fig. 5 Postoperative stem alignment assessment. Superimposed virtual plan (blue) and postoperative (red) stem models over the preoperative cadaveric femur model. Using a translational feature, The Hausdorff distance (HD) between the two implants in the coronal (**A**), sagittal (**B**), and axial (**C**) orientations was assessed. Note that the red stem is smaller (one size) due to the degree of varus and caudal malalignment.

Table 1 Results of individual dog's muscularity

Dog	Muscularity	Guide placement (ostectomy/broaching)	Surgical time (min)	Virtual stem size	Final stem size
1	4	Easy/difficult	52.7	9	9
2	2	Easy/easy	33.5	8	8
3	3	Easy/moderate	40.8	7	7
4	4	Moderate/difficult	50.4	8	7
5	3	Easy/difficult	47.7	9	9
6	1	Easy/easy	32.1	8	8
7	4	Easy/difficult	51.6	10	9

Note: Results of individual dog's muscularity (1 = severe atrophy, 2 = mild atrophy, 3 = normal, 4 = very muscular), difficulty of guide placement, total surgical time, virtual stem size and final stem size. (mm) = millimeter.

The ability to accurately predict implant size for THA is of paramount importance.[1–12] In this study, the implanted stem size matched the virtual plan exactly in 5/7 femurs, and was within one size in the remaining 2 femurs. In the two procedures in which the final stem size was one size smaller than the virtual plan, the smaller stem was selected intraoperatively because the broach met with the safety shelf of the broaching guide. Additionally, these two stems were malaligned in the frontal and sagittal planes. Therefore, the down-sized stems in the two cases reflect issues with canal-prep execution, rather than inconsistent preoperative planning. In addition to predicting stem size, this 3D virtual plan allowed for assessment of coronal, sagittal, and axial positioning of the femur for each case. This approach therefore overcomes the limitations of radiography, which can lead to variability associated with positioning of the femur.[5] Altering stem anteversion changes the concurrent two-dimensional geometry of the stem in the coronal and sagittal plane, and this is not accounted for with traditional radiographic templating. Although the purpose of the present study was not to compare the accuracy of the CAD virtual plan in predicting implant size to an accepted method of templating, such a comparison study may be warranted.

This study aimed to explore the feasibility of CSGs for THA, with the long-term goal of determining realistic applications and capabilities of CSGs in the clinical setting. The ostectomy guide was designed to ensure a smooth and controlled ostectomy height and orientation. In this study, characteristics of the ostectomy were not able to be adequately assessed due to image scatter artifact from the impacted stems in the postoperative models. The attempt to interpret variables such as stem height and HD distances to assess the ostectomy were

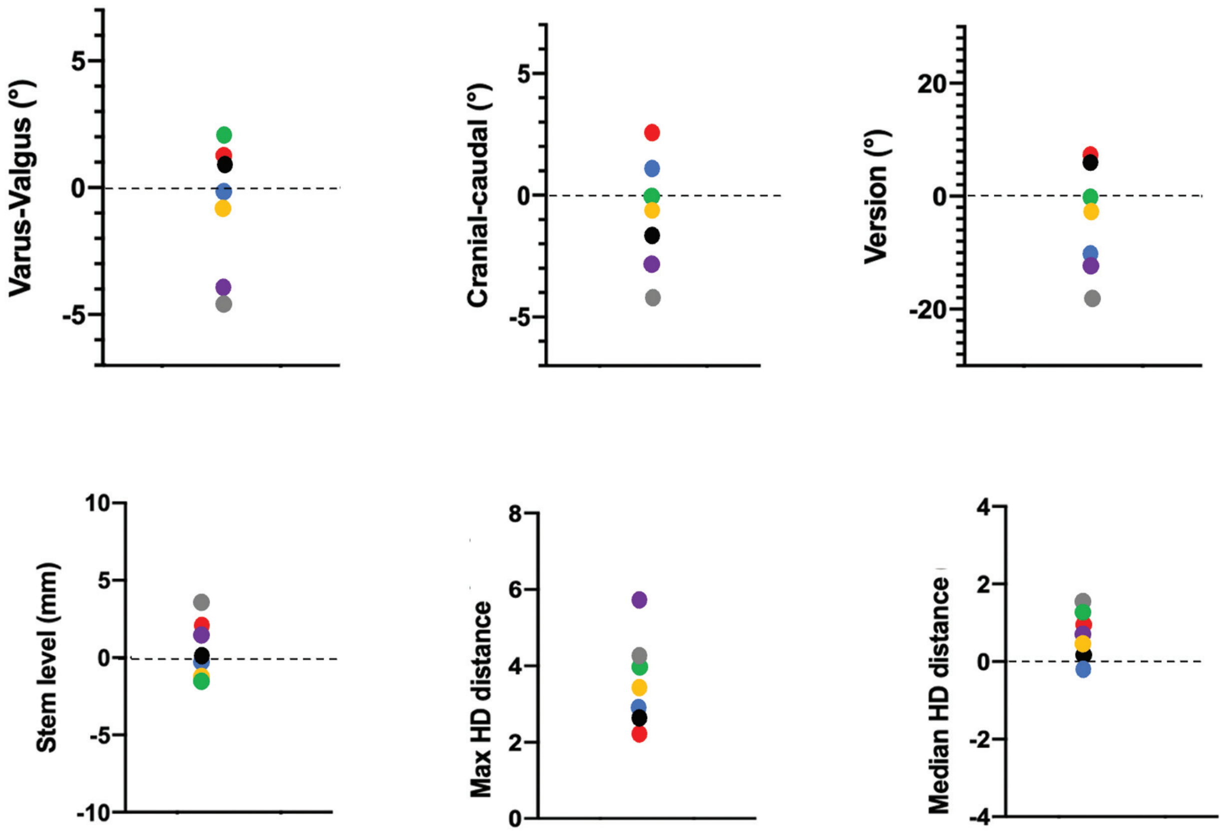

Fig. 6 Degree of error between pre- and postoperative implant placement. Each data point represents the degree of error measured for an individual dog (yellow = dog 1, red = dog 2, blue = dog 3, purple = dog 4, black = dog 5, green = dog 6, gray = dog 7).

ultimately not pursued due to the low number of cases, type 2 error, and the variability in virtual and final stem sizes in two cases. However, the use of the ostectomy guide was easy, fast when compared with the broaching guide, and subjectively added a significant degree of confidence. In the clinical setting, CSGs may be especially useful in cases with severe secondary changes and distorted anatomical landmarks.

The broaching guide was designed to give the surgeon visual references for controlling stem alignment in all three planes, rather than relying on assistant's visual references (in the sagittal plane). In our postoperative analysis, $Stem_{ax}$ had the greatest degree of error, where there was a tendency to place the stems in normo-version rather than the planned ante-version, which may predispose to changes in gait and medial patellar luxation in clinical patients. The potential reason why version was most inaccurate despite the availability of a version shaft is that normo-version is generally the path of least resistance during broaching, and small deviations from the plan are difficult to observe intraoperatively.

One potential benefit of the design explored in this study was the ability for the surgeon to rely solely on the broaching guide for alignment in all three planes. Clinical cases with excessive femoral procurvatum may benefit from CSGs as an alternative to relying on an assistant to determine sagittal alignment. Another feature of the broaching guide, its safety shelf, was created with the intention to help preserve craniomedial bone stock by giving a visual "warning" to the surgeon to lateralize broaching/rasping. However, canal preparation still requires an active effort that requires haptic feedback and early recognition of malalignment currently only gained through experience, something that was not able to be overcome by the safety shelf, as evident in two guided cases that required implantation of a smaller stem due to interference with the safety shelf.

The rationale for including an experienced board-certified surgeon and a resident was an attempt to demonstrate the accuracy of the guides in a representative spectrum of potential novice THA surgeons, rather than to distinguish differences between the two surgeons. A conflicting factor is that the resident (Jose Carvajal) was the primary designer of the guides and gained substantial familiarity with the press-fit system and procedure through the design process. Possible alternative study designs may demonstrate notable differences between surgeons, or between guided or free-handed procedures, especially if an independent guide designer is excluded from the surgical procedure.

The wide range in surgical time can be contributed to the additional time for soft tissue dissection and ensuring proper fit of the guides, especially the broaching guide. The longest surgeries were documented in the heavily muscled dogs with prominent quadriceps and gluteal musculature, which required a relatively more extensive vastus take-down, and imposed challenges by interfering with the drill post position of the broaching guide. In the clinical setting, patients with notable pelvic limb muscular atrophy may be better candidates for CSGs given the subjective easier fit and shorter surgical times of dogs with low muscularity scores in this study.

There are several limitations to our study: Cadaveric dogs do not adequately replicate many factors affecting femoral preparation and stem implantation that may be encountered in clinical cases. Additionally, only one guide design (one ostectomy and one broaching guide) was tested. Furthermore, the study was not sufficiently powered to find individual differences between surgeons, and despite surgery being performed by novice surgeons, the planning was verified by an experienced arthroplasty surgeon, likely affecting outcomes. Finally, potential benefits of 3D-printed guides should be weighted against the increased financial costs and the possibility of potential complications associated with increased surgical times, such as periprosthetic joint infections.[22] It should be mentioned that CSGs may give the false idea that the surgery is more accessible and can be performed without prior experience. Instead, the performance of these surgeries with CSGs requires considerable expertise, familiarity with the multiple anatomical, pathological, and CSG variables, as well as the ability to make unplanned intraoperative decisions. Ultimately, it is likely that this cohort is not reflective of some of the challenges encountered in clinical cases as the use of cadavers allows for less soft tissue resistance, better exposure and elevation of the femur, and lack of bony/periarticular pathology that affects stem implantation in clinical cases.

In summary, CT-based virtual templating may be a promising preoperative tool for THA in dogs, and implementation of CSGs resulted in acceptable accuracy of femoral stem placement without the occurrence of major intraoperative complications. Further investigation in the use of 3D model templating and the application of 3D CSGs by novice THA surgeons is encouraged prior to clinical application.

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Conflict of Interest
None declared.

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