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EXPERIMENTAL LAB RESEARCH

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Evaluation of 3D-printed patient-specific guides to facilitate fluoroscopic-assisted Kirschner wire stabilization of simulated capital physeal fractures in 3D-printed dog femur models

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Abstract

Objective: To compare the efficiency and accuracy of freehand and three-dimensionally printed (3DP) guide-facilitated fluoroscopic-assisted Kirschner wire placement in the femoral capitis performed by novice and experienced surgeons.

Sample population: 3DP models of five skeletally immature dog femurs were replicated.

Methods: Virtual surgical planning was done to position three parallel, virtual Kirschner wires inserted from the lateral subtrochanteric surface of the femur, coursing proximomedially through the femoral neck to engage the central capitis without penetrating the subchondral bone. Patient-specific guides were designed and 3DP to facilitate optimal Kirschner wire placement in each femoral model. Four faculty surgeons and four surgery residents performed freehand fluoroscopic-assisted wire placement in the femoral models. Wire placement was repeated ≥1 month later using the 3DP guides. Surgical time,

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number of times wires were redirected, number of fluoroscopy images acquired and Likert scores from the participants were recorded. Post-procedural CTs of the femur models were used to assess wire placement by 3D analysis.

Results: The number of fluoroscopy images was greater ($p < .001$) and procedure time was longer ($p < .001$) for freehand applications, while Likert scores were greater ($p < .001$) for 3DP-guide applications. Wire placement was more accurate with 3DP guides. Subchondral bone penetration occurred more frequently during freehand applications ($p < .01$).

Conclusion: 3DP patient-specific guides resulted in faster, simpler, and more accurate Kirschner wire placement than freehand placement for both novice and experienced surgeons. Further cadaveric and clinical studies are warranted to evaluate the utility of 3DP patient-specific guides to facilitate minimally invasive fluoroscopic-assisted femoral capital physeal fracture stabilization in dogs.

1 | INTRODUCTION

Femoral capital physeal fractures are typically stabilized with interfragmentary Kirschner wires in dogs.[1–4] The wires must be seated sufficiently in the capitis to afford stability, but can cause substantial trauma if advanced through the epiphyseal articular cartilage.[3–5] Capital physeal fracture stabilization has traditionally been performed via an open approach[1–3]; however, more recent reports describe minimally invasive, fluoroscopy-assessed reduction and stabilization.[3–7] Many capital physeal fractures can be accurately reduced in closed fashion by applying traction, abduction and slight internal rotation of the femur.[3,5] Kirschner wires can be placed percutaneously or via a limited approach to the subtrochanteric region of the femur.[4,5] The trajectory of the wire is assessed and adjusted using fluoroscopy.[5,7]

Fluoroscopic-assisted minimally invasive stabilization of capital physeal fractures is complicated by reliance on two-dimensional imaging to assess proper implant placement within the spherical femoral head.[8–10] Virtual surgical planning and application of patient-specific, three-dimensionally printed (3DP) guides are being utilized with increasing frequency in small animal orthopedics.[11–13] Three-dimensional-printed, patient-specific guides have been shown to facilitate accurate implant placement during orthopedic procedures.[11,14–16]

A recent study utilizing human femur models reported the use of custom 3DP drill guides to facilitate accurate screw placement during femoral neck fracture stabilization.[17] Application of this technology could prove useful when stabilizing capital physeal fractures in a minimally invasive fashion in dogs. The objective of the present study was to compare the efficiency and accuracy of freehand and 3DP patient-specific guide-facilitated fluoroscopic-assisted Kirschner wire placement to engage the femoral capitis performed by both novice and experienced surgeons in 3DP femoral models fabricated from computed tomography (CT) data obtained from skeletally immature dogs. Our hypotheses were that 3DP patient-specific guides would result in simpler, faster and more accurate Kirschner wire placement while reducing the number of fluoroscopic images taken during the procedure for both novice and experienced surgeons.

2 | MATERIALS AND METHODS

2.1 | Femoral model design and 3D printing

Pelvic and femoral CT (160-Slice Toshiba Aquillion CT Scanner; Cannon Medical Systems USA, Tustin, California) images (helical volume data, 0.5 mm slice thickness, slice overlap 0.3 mm) from five skeletally immature dogs were retrieved from the University of Florida Small Animal Hospital's radiographic image archive. The dogs were 6–12 months of age with open femoral physes, with femora measuring 18–22 cm in length. Digital Imaging and Communications in Medicine (DICOM) files of the CT images were imported into a computer software program (Mimics; Materialize NV, Leuven, Belgium) for three-dimensional (3D) modeling. The 3D rendered digital femora and a segment of the pelvis including the acetabulum were uploaded into 3D medical image processing software (3-matic, Materialize NV). The digital bone models (each dog's right femur and the largest diameter corresponding acetabulum) were labeled and the stereolithography (.STL) files were transferred to a 3D printing program (Insight, Stratasys, Eden Prairie, Minnesota) to generate toolpaths for printing.

The toolpath settings were adjusted using three outer contours (0.78 mm each layer thickness) with an interior fill using a double dense sparse (cell size 2.54 mm) pattern. Bone models were printed (Fortus 450mc, Stratasys) with a T12 tip in a biocompatible acrylonitrile butadiene styrene (ABS) material, with a final print accuracy of ±0.127 mm.

The independent models of femoral epiphysis and the remaining corresponding femur were anatomically reduced and glued in place using a contact adhesive (Goop Contact Adhesive, Los Angeles). A total of 16 replicates of each of the five femoral models were fabricated for Kirschner wire placement.

2.2 | Design and 3D printing of the patient-specific guides

All guides were designed based on the 3D rendered digital femora using the 3D medical image processing software. Three parallel, 1.6 mm diameter cylinders, representing virtual Kirschner wires, were inserted from proximal–to–distal in the lateral subtrochanteric region of the proximal femur.[18] The proximal tip of each virtual Kirschner wire was positioned centrally in the thickest region of the epiphysis, 2 mm subjacent to the margin of the subchondral bone. The virtual Kirschner wires were separated by a minimal distance of 1.6 mm (Figure 1).

Drill guide design consisted of three patient-specific Kirschner wire sleeves and a guide body with a patient-specific base. Three cannulated, cylindrical drill sleeves were designed to accommodate 1.6 mm-diameter Kirschner wires with an internal diameter of 1.8 mm, external diameter of 4 mm and length of 40 mm. The drill guide body was designed by creating a trapezoidal base that enveloped the drill sleeves. The base extended proximally, encompassing the third trochanter, with the block extending 20 mm laterally. The block provided sufficient mass to allow the user to manipulate the guide during the procedure. Spheres were added to enlarge the footprint of the guide around the cranial and caudal femoral cortex. Once the guide was shaped to conform to the dimensions of each individual dog's proximolateral femur to afford sufficient contact in the desired location, the topography of the third trochanter and subtrochanteric region of the lateral femur were subtracted from the medial surface of the base by means of Boolean subtraction with a clearance factor of 0.3 mm from the modular template to create a patient-specific fit for each bone model (Figure 1).

The resultant. STL files were 3D printed (Form 3B SLA Printer, Formlabs, Somerville, Massachusetts) with 0.1 mm layers of a surgical guide resin (Surgical Guide Resin, Formlabs). After printing, the support material was removed, the guides were washed with alcohol (15 min) and subsequently cured at 60°C (30 min) (Form Wash & Form Cure, Formlabs).

2.3 | Participants

Four faculty small animal orthopedic surgeons and four small animal surgery residents (one first-year, two second-year, and one third-year) participated in this study. Each individual was asked to estimate the number of open and minimally invasive capital physeal fracture repairs they had performed or assisted with during their careers.

2.4 | Procedures

Orthogonal view 3D constructed images of each individual femur with optimal parallel placement of three Kirschner wires were shown to each participant to emulate prior to beginning each procedure.[18] Each participant performed Kirschner wire placement in each of the five femoral models using two application methods: freehand and 3DP guide-assisted. Participants performed the freehand method in an initial session and then performed the 3DP guide-assisted method in a second session. The two sessions were separated by a minimum of 4 weeks to mitigate the influence of prior experience gained during the initial session. Fluoroscopy (Fluoroscan InSight Mini-C-arm: Hologic, Diagnostic Health Care Systems, Raleigh, North Carolina) was used during all procedures and participants were allowed to image the femur at any angle deemed useful. All operating room personnel wore lead aprons and thyroid shields throughout the entirety of each session.

The reduced femoral models were placed into a quadrangular 3DP ABS tray containing a secured acetabular model and were partial immersed in liquified ballistic gel which was allowed to solidify to simulate the regional musculature. The lateral surface of the proximal one-third of the femur and the remainder of the distal femur were not embedded within ballistic gel and remained exposed.

During freehand procedures, three Kirschner wires were inserted, without the use of a 3DP guide, into the subtrochanteric region and advanced into the femoral

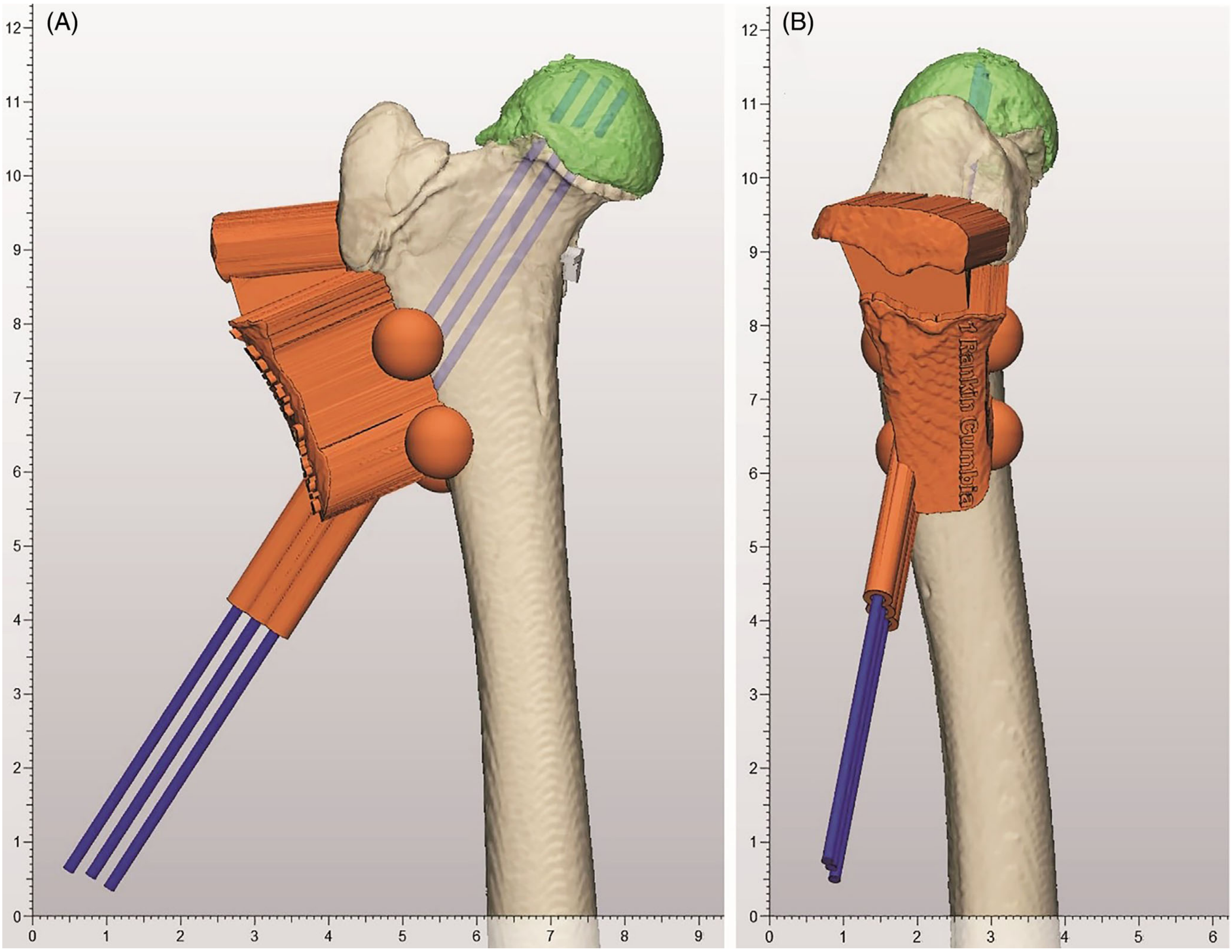

FIGURE 1 Three dimensional (3D) design of a patient-specific guide in the 3D medical image processing software. (A) Craniocaudal view, (B) lateromedial view. The three-dimensionally printed (3DP) patient-specific guide is designed on a virtually reduced slipped femoral capital physeal fracture after the virtual Kirschner wire placement. Femoral capitis is green. Blue cylinders represent the three parallel Kirschner wires.

neck and epiphysis. Fluoroscopy was used at the participants' discretion throughout each procedure to assess wire placement, trajectory, and depth. The initial Kirschner wire was inserted in the subtrochanteric region of the lateral cortex of the femur and the femur was imaged. Participants were permitted to remove, redirect, and reposition the wire as needed. The Kirschner wire was advanced into the femoral neck and ultimately seated in the epiphysis. Manipulation of the femur within the acetabulum was also utilized to help ascertain that a wire had not penetrated the subchondral surface of the capitis. If the participant perceived that a wire had penetrated the articular epiphyseal subchondral bone, based on manipulation of the femur of fluoroscopy, the participant was permitted to withdraw the wire to rectify the penetration. After the initial wire had been placed, the participants were allowed to cut the protruding portion of the wire before placing the second and third wires in similar fashion.

In the 3DP guide group, the planned drilling depths of virtual Kirschner wires were measured on the 3D software for each virtual model. Individual Kirschner wires were marked with different colored permanent markers to indicate optimal depth of insertion based on the virtual surgical plan; red was used for the proximal Kirschner wires, blue for the central and green for the distal Kirschner wires. During the procedure, the guide was positioned in the intended location on the subtrochanteric region of the lateral femur and the Kirschner wires were sequentially inserted thorough the drill towers on the guide (Figure 2). Fluoroscopy was again used at the discretion of the participants to confirm proper trajectory and depth of Kirschner wire placement (Figure 3). Manual manipulation of the femur within the acetabulum

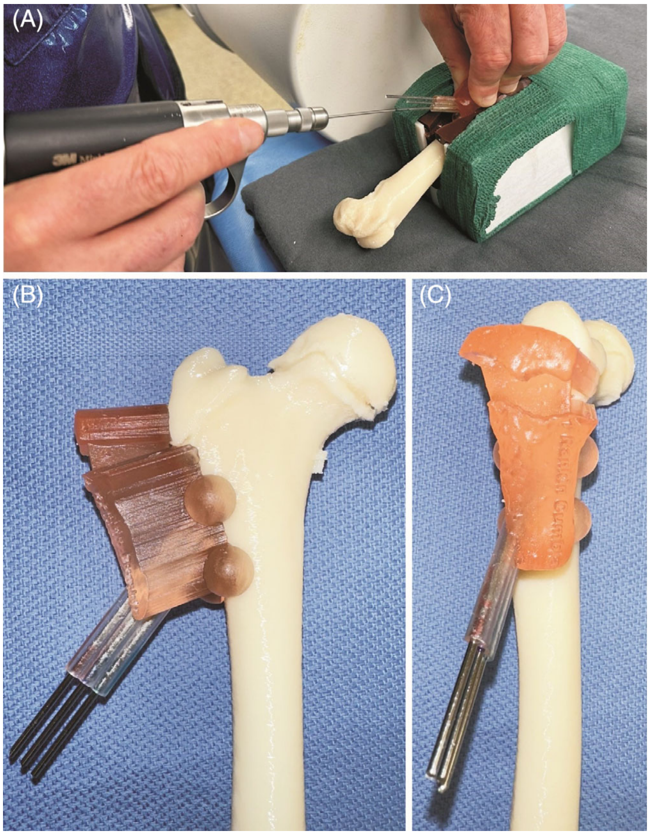

FIGURE 2 Femoral capital physeal fracture bone model drilling application using three-dimensionally printed (3DP) patient-specific guide. The three-dimensional (3D) printed rectangular tray and brown ballistic gel covered the proximal femur and the guide was positioned in the intended location over the subtrochanteric region of the lateral femur (A). The Kirschner wires were sequentially inserted through the drill towers on the guide. Post-procedural craniocaudal (B) and lateromedial (C) images of the femur bone model with the guide in place.

was again utilized to help determine whether or not the Kirschner wires had penetrated the articular subchondral bone surface of the epiphysis.

2.5 | Post-procedure assessment

Surgical time, the number of attempts to obtain accurate Kirschner wire placement, number of times the wires were redirected during wire placement, the number of fluoroscopy images obtained, and comments from the participants were recorded at the end of each procedure. Each participant assigned a Likert score with their perception of the ease of the procedure using a 10-point scale: 0 = very difficult; 5 = moderately difficult; and 10 = very simple.

After the procedures, CT studies of the models were obtained and imported into the 3D medical image processing software program. The insertion points in the lateral femoral cortex and the position of the implanted tip of each Kirschner wire in the femoral capitis were compared between each virtual and implanted wires using 3D analysis (Figures 4 and 5). An engagement ratio, defined by the length of the virtual or implanted Kirschner wire that protruded into the femoral capitis beyond the physeal border (Figure 6), divided by the thickness of the femoral capitis along the trajectory of the virtual or implanted Kirschner wire, was calculated for each Kirschner wire. Wires breaching the cortex of the femoral neck or penetrating the surface of the subchondral bone of the capitis were also noted (Figure 4). The fluoroscopy-assisted procedure allowed the participants to know if any of the wires went into the hip joint by perforating the subchondral bone and to pull it back. Thus, there were no wires left protruding from the capitis, after the procedures.

2.6 | Statistical analysis

Statistical analyses were performed using SPSS (version 26.0, IBM corporation, Armonk, New York). A preliminary power analysis was performed to assign the minimum sample size. Data were tested for normality using the Shapiro–Wilk test. Descriptive statistics were used to report results in terms of median and range or mean and standard deviation (SD). The normal distributed variables were compared between the freehand and 3DP patient-specific guide groups using the student's *t*-test. Likert scores were compared using Mann Whitney U test. The Wilcoxon rank sum test was used to compare groups for the data which were not normally distributed. Statistical significance was set at $p < .05$.

3 | RESULTS

The faculty surgeons had significantly greater experience than the residents with both open and minimally invasive capital physeal fracture stabilizations ($p < .01$ and $p < .05$, respectively). The residents estimated that they had participated in a mean ± SD of 0.5 ± 0.5 open, and 1.0 ± 0.7 minimally invasive capital physeal fracture stabilization procedures. The faculty surgeons estimated that they had participated in or performed a mean ± SD of 35.3 ± 38.8 open, and 1.8 ± 0.8 minimally invasive capital physeal fracture stabilization procedures.

3DP guide-assisted wire placement resulted in a nearly five-fold decrease in the mean number of fluoroscopy images (21–5 images) obtained ($p < .001$) and reduced the mean procedure time by >50% (8.5–3.5 min)

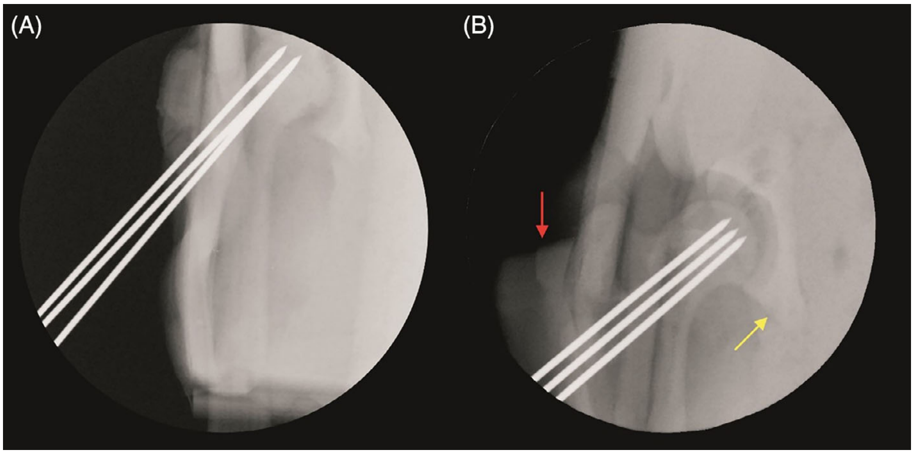

FIGURE 3 Craniocaudal fluoroscopy images of the bone model after placing three Kirschner wires ([A]: Freehand application, [B]: three-dimensionally printed [3DP] patient-specific guide application). The external and internal structure of the femur bone model can be distinguished, as well as the physeal border. The 3DP patient-specific guide (red arrow) allows the femoral cortex and Kirschner wires to be seen, as well as the 3DP acetabulum model (yellow arrow). Freehand Kirschner wire placement resulted in non-parallel alignment of the Kirschner wires with greater discrepancies in the locations of the insertion point and implanted tip the Kirschner wires relative to the planned virtual locations.

($p < .001$) compared to freehand applications across all participant groups (Table 1). Median (and range) Likert scores for the procedure difficulty were 6 (2–9) for the freehand technique and 9 (8–10) for the 3DP guide-assisted applications for all participants. Median (and range) faculty Likert scores were 7 (4–9) for freehand technique and 10 (9–10) for the 3DP guide-assisted applications. Median (and range) resident Likert scores were 6 (2–9) for freehand technique and 9 (8–10) for the 3DP guide-assisted applications. Participants found the 3DP guide-assisted applications to be easier than the freehand technique, as Likert scores (Table 1) were significantly greater for 3DP guides applications across all participant groups ($p < .001$). There was no statistical difference between the residents and faculty surgeons with respect to Likert scores, the number of attempts at placing Kirschner wires, number of fluoroscopy images taken during each procedure and procedure time. Kirschner wires were redirected a median (and range) of 2 (0–22) times during freehand procedures, while wires were not redirected during 3DP guide applications ($p < .001$). Five participants commented that interference with a previously placed Kirschner wire impeded subsequent freehand wire placement.

All participants stated that the 3DP guides were useful and conformed accurately to the lateral surface topography of the femurs, although four participants commented that one of the 3DP guides did not securely lock into place on the femur. All participants felt that freehand applications resulted in acceptable wire placement, but that the 3DP guides simplified the procedure. Five participants stated that having the distal femur exposed simplified wire placement, especially during the freehand applications.

Post-procedure 3D analyses revealed the point of insertion of all three (inserted most proximal, central, and distal on the femur) Kirschner wires was closer to the virtually planned location for the 3DP guide applications than with freehand placement for both faculty and residents ($p < .001$) (Table 2). The tip of the central and distal wires placed with the 3DP guide were significantly closer to those wires' virtual locations for faculty surgeons ($p < .01$), while the location of the tip of resident-placed wires did not differ significantly ($p > .05$) between application methods (Table 2).

Kirschner wire femoral head engagement ratios were only different between the freehand and 3DP guide groups for the proximal wire placed by the residents; the engagement ratio was greater for wires placed by residents using the 3DP guide than wires placed with the freehand technique ($p < .01$) (Table 3). The distance from the implanted tip of each Kirschner wire to the margin of the subchondral bone surface was greater in the freehand group than in the 3DP guide-assisted group for the proximal wire ($p < .05$), but not for the central and distal Kirschner wires ($p > .05$) for faculty and residents combined. When comparing faculty to residents, the 3DP guide-assisted technique resulted in the proximal Kirschner wires being inserted significantly closer ($p < .05$) to the surface of the subchondral bone compared to freehand applications for the residents and in the distal wires for faculty. Kirschner wires breached the cortex of the femoral neck more commonly during freehand applications ($n = 27$) than during 3DP guide-assisted applications ($n = 3$) across all

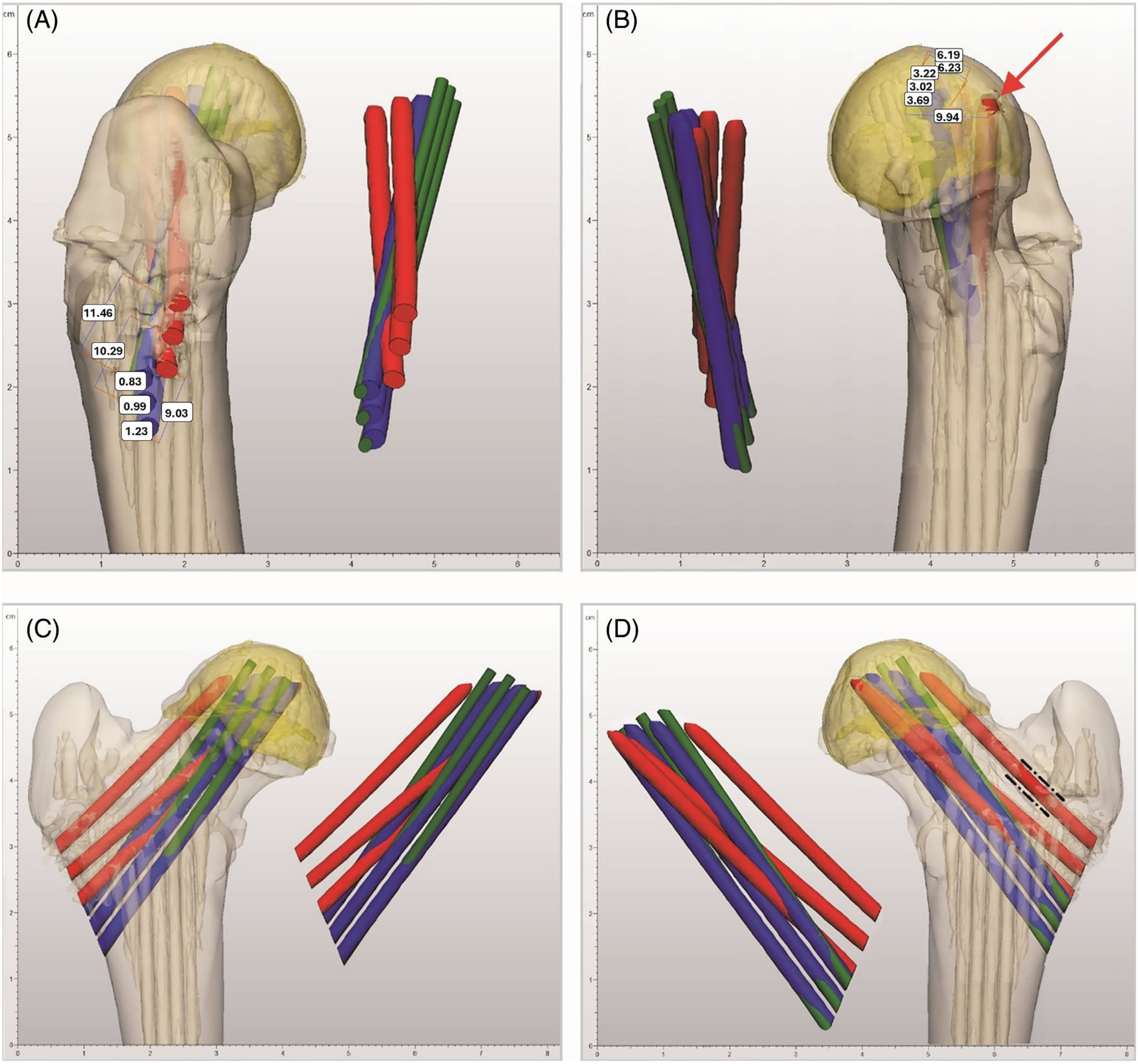

FIGURE 4 Post-procedural three-dimensional (3D) analysis of the three Kirschner wires in one femur placed using freehand (red) and three-dimensionally printed [3DP] patient-specific guide (blue) applications compared to the planned optimal virtual Kirschner wire placement (green). The Kirschner wires are illustrated with and without the bone model in the 3D medical image processing software. The measurements and appearance of the three Kirschner wires placed using freehand application (red) and 3DP patient-specific guide application (blue) reveal a significant discrepancy of the insertion points ([A], lateromedial view) and implanted tip ([B], mediolateral view) of the Kirschner wires relative to the virtual plan. The craniocaudal (C) and caudocranial (D) views show the location of the Kirschner wires. The mediolateral view (B) shows a Kirschner wire (red arrow: Red, freehand application, distal wire) penetrating to the subchondral bone surface of the femoral head and the caudocranial view (D) shows the wire breached the cortex of the femoral neck (between the two black broken lines: Red, freehand application, proximal wire).

participants ($p < .001$) (Table 4). Similarly, Kirschner wires penetrated the articular surface of the femoral head more frequently during freehand applications ($n = 16$) than during 3DP guide-assisted applications ($n = 4$) ($p < .01$). Kirschner wires placed by residents penetrated the articular surface of the femoral head ($n = 12$) more frequently than wires placed by faculty ($n = 4$) during freehand applications ($p < .01$). Penetration of the articular surface of the femoral head also occurred more frequent for the residents ($n = 4$) than the faculty ($n = 0$) during the 3DP guide-assisted applications ($p < .01$).

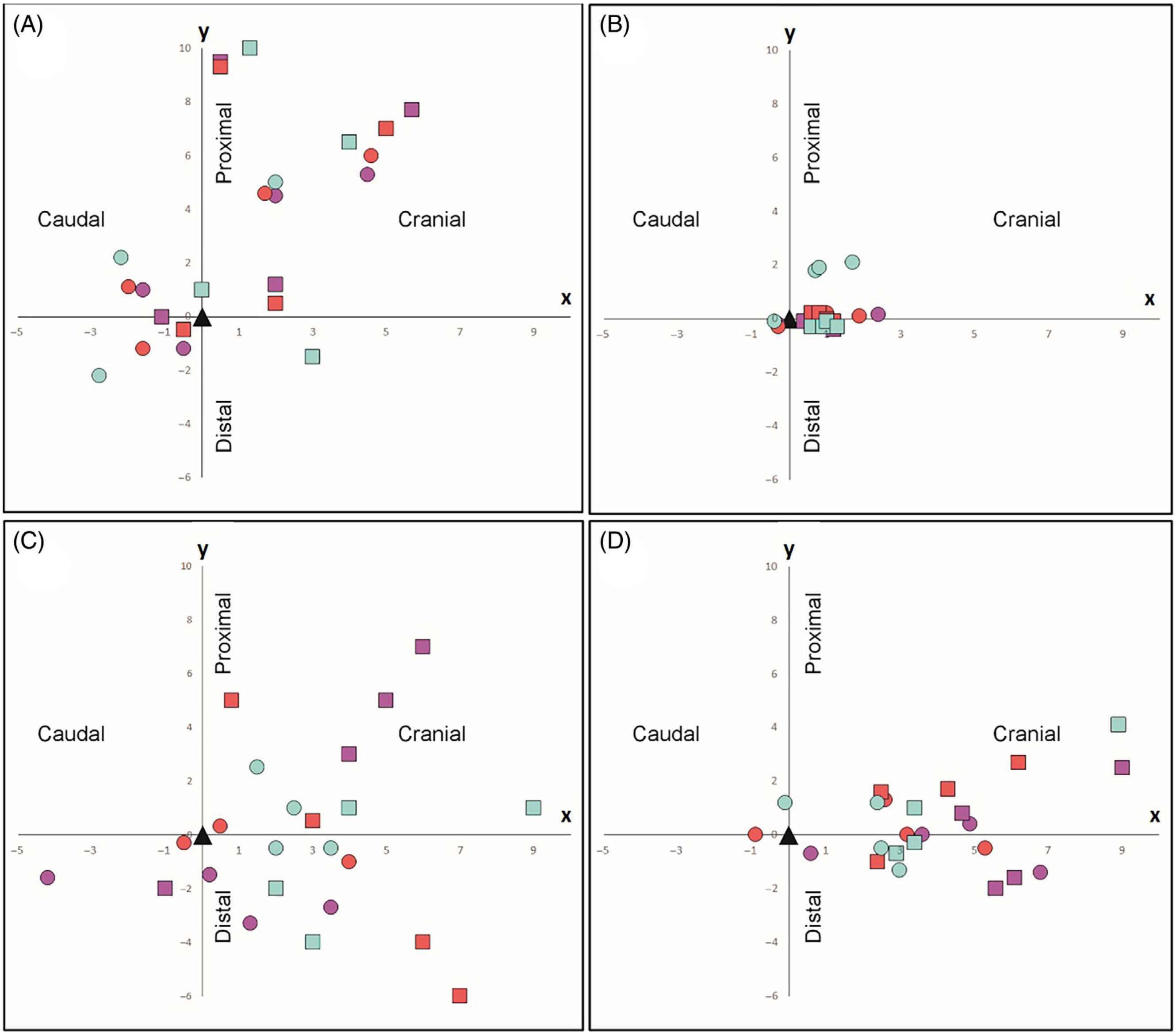

FIGURE 5 Distribution of the insertion points ([A]: Freehand, [B]: three-dimensionally printed [3DP] guide) and the implanted tip ([C]: Freehand, [D]: 3DP guide) of the three parallel Kirschner wires in terms of the cranial, caudal, proximal and distal directions in a single three-dimension (3D) printed femur specimen (as illustrated in this figure). The triangle represents the planned insertion point or tip of the virtual Kirschner wire. The squares represent the insertion points or implanted tips of the Kirschner wires placed by faculty surgeons and the circles represent those placed by residents. Proximal, central and distal Kirschner wires are colored red, blue and green, respectively.

4 | DISCUSSION

The present study compared the accuracy and efficiency of fluoroscopic-assisted Kirschner wire placement for capital physeal fracture stabilization with and without 3DP patient-specific guides in 3DP dog femoral models, performed by both novice and experienced participants. Our results supported our hypothesis, as the application of 3DP patient-specific guides reduced procedure time, difficulty of the procedure, number of fluoroscopy images, and improved accuracy of Kirschner wire placement for both novice and experienced participants.

As expected, faculty surgeons had greater experience stabilizing slipped capital femoral physeal fractures than residents. This disparity was expected to result in significant differences in outcome measures between the two participant groups during the freehand applications, and use of the 3DP guides was expected to mitigate differences between the two participant groups. Interestingly, there were fewer differences than expected between the performance of the faculty surgeons and residents with both applications and the number of attempts needed to obtain acceptable parallel Kirschner wire placement was not different between participant groups for either application technique. Penetration of the epiphyseal subchondral bone margin was primarily ascribed to advancing the wire too deeply into the capitus and was impacted less by the trajectory of the Kirschner wire. The lack of disparity with regard to the number of attempts to obtain accurate Kirschner wire placement between residents and the faculty surgeons was attributed to the residents preferring to redirect Kirschner wires while faculty were more inclined to remove and reinsert a poorly placed wire.

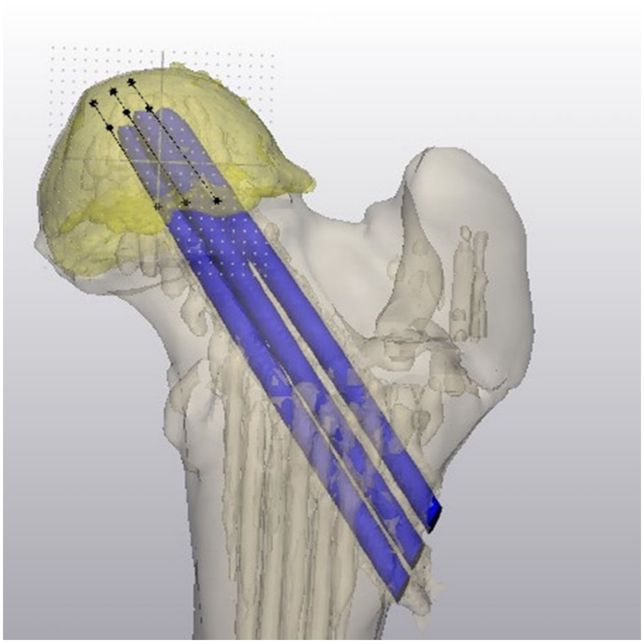

FIGURE 6 Measurements (between black stars of each line) to determine Kirschner wire engagement and the distance between the implanted tip of the Kirschner wires and the articular margin of the subchondral bone used to calculate engagement ratios (%). The proximal femur is shown using the transparency function, with the femoral head and physeal border depicted in yellow.

Redirection and assessment of the advancement of the Kirschner wires during the freehand applications resulted in the acquisition of more fluoroscopy images than 3DP guide-assisted procedures. Consequently, procedure time for freehand applications was longer, regardless of the participant's experience. Use of the 3DP guides reduced fluoroscopy imaging, as none of the Kirschner wires needed to be redirected with this technique. The depth that each Kirschner wire should be seated in the femur was also marked on individual wires which also reduced the need for repeated imaging as the wire was advanced. Reduced fluoroscopy use lessens radiation exposure for the operators and reduces surgical time. Reduced anesthetic time has been associated with a reduced risk of surgical site infections and anesthetic complications.[19] Additionally, occupational radiation exposure to orthopedic surgeons is a known concern, and has been suggested to increase the risk of developing cancer compared to other healthcare workers by fivefold.[19–22] Therefore, reduction of surgical time and fluoroscopy use with the application of 3DP guides would be beneficial to both patients and surgeons.

Freehand applications had lower Likert scores indicating that the participants perceived the technique to be more difficult, whereas Kirschner wire placement using the 3DP patient-specific guides was perceived to be easier, regardless of the participant's level of experience. Participant comments revealed that freehand applications generally resulted in acceptable Kirschner wire placement, but were not as accurate or predictable as placing wires with 3DP guides. Targeting the desired Kirschner wire insertion point, termination of drilling depth and interference with previously placed Kirschner wires, contributed to increased difficulty and less efficiency during freehand applications.

TABLE 1 Summary of the number of fluoroscopic images taken, procedure time and the subjective difficulty (lower Likert scores) or easy (higher Likert scores) of the procedure.

Participant group	Application method	Number of total fluoroscopy images	Procedure time (minutes)	Procedure difficulty (Likert scores)
Faculty surgeons	Freehand	^{a}20 (13–50)	^{a}7.8 (5–22.4)	^{a}7 (4–9)
	3DP guide	^{b}5 (3–7)	^{b}3.2 (2.2–6.1)	^{b}10 (9–10)
Residents	Freehand	^{a}21 (14–30)	^{a}8.9 (6.1–18.7)	^{a}6 (2–9)
	3DP guide	^{b}5 (2–7)	^{b}3.7 (3.2–6.2)	^{b}9 (8–10)
All participates	Freehand	^{a}21 (13–50)	^{a}8.5 (5–22.4)	^{a}6 (2–9)
	3DP guide	^{b}5 (2–7)	^{b}3.5 (2.2–6.2)	^{b}9 (8–10)
Significance*		$p < .001$	$p < .001$	$p < .001$

Note: All data reported as median (range) for individual procedures.

Abbreviation: 3DP, three-dimensionally printed.

*Results in each column are significantly different, $p < .05$, if the paired outcome do not share the same superscript letter.

TABLE 2 Summary of the discrepancy (mm) between the planned virtual and post-procedural locations of the insertion point and implanted tip of the proximal, central and distal Kirschner wires (mean ± SD).

Participant group	Application method	Insertion points of the proximal wires	Insertion points of the central wires	Insertion points of the distal wires	Implanted tip of the proximal wires	Implanted tip of the central wires	Implanted tip of the distal wires
Faculty surgeons	Freehand	[a]6.60 ± 4.01	[a]6.90 ± 4.28	[a]7.50 ± 4.12	3.50 ± 1.73	[a]3.70 ± 2.43	[a]3.70 ± 2.13
	3DP Guide	[b]0.79 ± 0.52	[b]0.70 ± 0.57	[b]0.85 ± 0.59	2.35 ± 0.99	[b]2.35 ± 1.31	[b]2.60 ± 1.54
Significance*		$p < .001$			$p > .05$	$p < .01$	$p < .01$
Residents	Freehand	[a]8.35 ± 5.21	[a]9.05 ± 5.54	[a]9.55 ± 5.62	3.65 ± 2.35	3.95 ± 1.54	4.20 ± 2.07
	3DP Guide	[b]1.1 ± 0.72	[b]1.0 ± 0.83	[b]1.0 ± 0.69	2.9 ± 2.46	3.2 ± 1.74	3.5 ± 2.16
Significance*		$p < .001$			$p > .05$	$p > .05$	$p > .05$
All participants	Freehand	[a]7.48 ± 4.67	[a]7.98 ± 2.01	[a]8.53 ± 4.98	[a]3.58 ± 7.04	[a]3.83 ± 2.01	[a]3.95 ± 2.09
	3DP guide	[b]0.95 ± 0.64	[b]0.88 ± 0.72	[b]0.95 ± 0.64	[b]2.65 ± 2.87	[b]2.78 ± 1.58	[b]3.08 ± 1.91
Significance*		$p < .001$			$p < .05$	$p < .01$	$p < .05$

Abbreviation: 3DP, three-dimensionally printed.
*Results in each column are significantly different, $p < .05$, if the paired outcome do not share the same superscript letter.

TABLE 3 Summary of the individual wire engagement ratios (%) and the distance (mm) between the implanted tip of the Kirschner wires and the articular surface of the subchondral bone (mean ± SD, range).

Participant group	Application method	Wire engagement ratio in the femoral head (%) (proximal, central and distal wires, respectively)			Wire tip distances to subchondral bone (mm) (proximal, central and distal wires, respectively)		
Faculty surgeons	Freehand	0.70 ± 0.10	0.68 ± 0.14	0.64 ± 0.15	3.25 ± 1.07	3.15 ± 1.46	[a]3.10 ± 1.45
	3DP guide	0.70 ± 0.09	0.71 ± 0.08	0.73 ± 0.11	3.05 ± 0.76	2.65 ± 0.67	[b]2.15 ± 0.99
Significance*		$p > .05$	$p > .05$	$p > .05$	$p > .05$	$p > .05$	$p < .05$
Residents	Freehand	[a]0.71 ± 0.11	0.71 ± 0.19	0.70 ± 0.18	[a]3.00 ± 1.17	2.80 ± 2.04	2.50 ± 1.64
	3DP guide	[b]0.8 ± 0.11	0.7 ± 0.09	0.7 ± 0.11	[b]2.1 ± 3.12	2.4 ± 2.88	2.3 ± 2.88
Significance*		$p < .01$	$p > .05$	$p > .05$	$p < .05$	$p > .05$	$p > .05$
All participants	Freehand	0.70 ± 0.10	0.70 ± 0.17	0.67 ± 0.17	[a]3.13 ± 1.11	2.98 ± 1.76	2.80 ± 1.56
	3DP guide	0.75 ± 0.11	0.73 ± 0.09	0.72 ± 0.11	[b]2.58 ± 1.06	2.53 ± 0.78	2.25 ± 0.93
Significance*		$p > .05$	$p > .05$	$p > .05$	$p < .05$	$p > .05$	$p > .05$

Abbreviation: 3DP, three-dimensionally printed.
*Results in each column are significantly different, $p < .05$, if the paired outcome do not share the same superscript letter.

Predictability of wire placement is particularly important when attempting to place three, parallel Kirschner wires, as accurate parallel placement reduces the potential for interference and the need to redirect during placement of the second and third wire. Accuracy of wire placement when using the 3DP guides is dependent on the guide locking precisely on the bone model in the intended location. Thus, a common clinical concern for surgeons is the secure fit of the 3DP guide when applied to the bone during surgery. In the present study, several participants commented that one of the guides did not lock securely in place on the femoral model, although based on the resultant wire placement the guide design appeared to function effectively, facilitating accurate and predictable Kirschner wire placement. The 3DP guides were designed to conform to the surface topography of the proximolateral femur, but the lateral subtrochanteric surface of the femur is relatively smooth and cylindrical which can precipitate inaccurate circumferential placement of the guide. Consideration should be given to increasing the diameter of the spheres attached to the base of guides in future applications to incorporate more of the cranial and caudal femoral topography. The guide could also extend proximally to incorporate more of the

TABLE 4 Summary of Kirschner wires that breached the cortex of the femoral neck or penetrated the subchondral bone surface of the femoral head (count, percentage, mean ± SD).

Participant group	Application method	Wire breaching the cortex of the femoral neck	Wire perforation the femoral head
Faculty surgeons	Freehand	12/20 (60%) [a]0.7 ± 1.2	4/20 (20%) [a]0.2 ± 0.4
	3DP guide	0/20 (0%) [b]0.0 ± 0.0	0/20 (0%) [b]0.0 ± 0.0
Significance*		$p < .001$	$p < .001$
Residents	Freehand	15/20 (75%) [a]0.8 ± 0.9	12/20 (60%) [a]0.6 ± 0.7
	3DP guide	3/20 (15%) [b]0.1 ± 0.4	4/20 (20%) [b]0.2 ± 0.4
Significance*		$p < .01$	$p < .05$
All participants	Freehand	27/40 (67.5%) [a]0.8 ± 1.1	16/40 (40%) [a]0.4 ± 0.6
	3DP guide	3/40 (7.5%) [b]0.1 ± 0.3	4/40 (10%) [b]0.1 ± 0.3
Significance*		$p < .001$	$p < .01$

Abbreviation: 3DP, three-dimensionally printed.
*Results in each column are significantly different, $p < .05$, if the paired outcome do not share the same superscript letter.

greater trochanter to ensure a more distinctive and secure fit during clinical applications, but the insertions of the gluteal muscles on the greater and third trochanter might limit the effectiveness of this design modification. While the 3DP guides resulted in wire insertion very close to the target position, the discrepancies of the terminal tip of wires placed freehand and with 3DP guides from the targeted endpoint for the residents were similar. Greater surgeon experience may improve the accuracy of 3DP guide placement on the proximal femur which is critical as even minor discrepancies in positioning of the 3DP guide could result in notable differences in wire trajectory or the tip of the wires location. In addition, greater experience placing wires with a drill might have contributed to the superior accuracy of the faculty surgeons. Altering the guide to ensure a more secure fit may improve the accuracy of guide-assisted wire placement for novice surgeons.

De Moya et al. noted that the risk of one or more wires penetrating the epiphyseal articular cartilage is accentuated during minimally invasive capital femoral physeal fracture stabilization due to the small size and spherical morphology of the femoral capitis and the inability to visually or palpably inspect the articular surface of the epiphysis.[5] While the adverse consequences of a wire or wires protruding through the articular surface of the femoral head is well documented,[4,5,10,23] the clinical impact of a wire perforating the cortex of the femoral neck is unknown and may not be detrimental. In the present study, penetration of the femoral head occurred more frequently during freehand applications than 3DP guide applications, with residents penetrating the subchondral bone margin of the femoral head more frequently than faculty during freehand applications. The application of 3DP guides reduced the number of inadvertent femoral capitis penetration for both residents and faculty surgeons, demonstrating the value of these guides when used by both novice and experienced surgeons. Similarly, breaching of the cortical surface of the femoral neck also occurred more frequently during freehand applications than 3DP guide applications, with the residents breeching the cortex of the neck more frequently than faculty during freehand applications. The use of 3DP guides reduced the number of femoral neck breaching for both residents and faculty surgeons.

Limitations of the current study include the use of isolated 3DP femora models instead of skeletally immature dog cadavers. Kirschner wire placement was admittedly simpler in the bone models than a cadaver with an intact pelvic limb and the surrounding musculature. We attempted to mitigate this deficiency by partially encasing the femurs in ballistic gel, but several participates commented that exposure of the distal femur simplified freehand wire placement. The models, however, allowed us to provide multiple uniform replicates of each femur reducing variability between procedures and participants. The participants commented that haptic feedback during wire placement in the 3DP bone models was realistic. Although the 3DP bone models used in our study are of our own design, the study did not focus on the realism of 3DP femoral bone models. A recent study reported that their 3DP temporal bone model was highly similar to the natural temporal bone, and suggested that the model could be conveniently and effectively used in the training of novice surgeons.[24] The capitis was orthotopically positioned in all of the 3DP bone models; however, in a clinical situation the guides might be rendered ineffective if reduction of the capitis is poor. Accurate reduction can be particularly challenging due to limited visualization and manipulation of the fracture site, and soft tissue interference, whether using minimally invasive or open techniques. The surgeon's skills and experience may also affect the performance. Fortunately, anatomic reduction of most capital physeal fractures is attainable in a closed fashion. De Moya et al. reported that reduction was deemed anatomic in 10/13 and acceptable in 3/13 capital physeal fractures stabilized minimally invasively.[5] In addition, guides might not fit as accurately or securely in vivo due to the presence of periosseous soft tissues which are not modeled during virtual planning.[13,17,25,26] Our use of permanent marker to demarcate the depth of Kirschner wire insertion is another potential limitation of the current protocol, as the markings might become obscured during sterilization for clinical cases. Alternatively, the length of the protruded segment of each wire, as predetermined during virtual planning, could be measured intra-operatively with a ruler or a segment of wire cut to the length representative of the protruding portion of each wire prior to surgery and sterilized. Potentially an inverted depth gauge could be designed and 3D printed to measure the length of the implanted portion of each Kirschner wire.

The results of the present study suggest that the use of 3DP patient-specific guides would be advantageous to facilitate accurate and efficient Kirschner wire placement during fluoroscopic-assisted minimally invasive femoral capital physeal fracture stabilization in dogs. The 3DP guides proved to be beneficial for both experienced and novice surgeons. The use of 3DP guides would likely reduce surgical time, procedure difficulty, and fluoroscopy use, as well as simplify fracture stabilization. The use of 3DP patient-specific guides would, however, require acquisition of a preoperative CT scan and designation of additional time to design and print the guides prior to surgery which would increase costs for owners and could delay surgical intervention. Further cadaveric and clinical studies are warranted to evaluate the efficacy of 3DP patient-specific guides in facilitating fluoroscopic-assisted femoral capital physeal fracture stabilization in dogs.

AUTHOR CONTRIBUTIONS

Deveci MZY, DVM, PhD: Contributed to the design of the study, identified and retrieved suitable medical records, provided procedural photographs, compiled all data, analyzed data for statistical significance, interpreted data, drafted and revised the manuscript. Lewis DD, DVM: Contributed to the conception and design of the study, performed the procedures, oversaw data collection, revised the manuscript and provided scientific, in-line editing of the manuscript. Worden NJ, DVM, MS: Performed the procedures, revised the manuscript and provided scientific, in-line editing of the manuscript. Johnson MD, DVM, MVSc: Performed the procedures, revised and provided scientific, in-line editing of the manuscript. Scheuermann LM, DVM, MS: Performed the procedures, revised and provided scientific, in-line editing of the manuscript. Kim SE, BVSc, MS: Performed the procedures, revised and provided scientific, in-line editing of the manuscript. Peterson LC, DVM: Performed the procedures, revised and provided scientific, in-line editing of the manuscript. All authors provided a critical review of the manuscript and endorse the final version. All authors are aware of their respective contributions and have confidence in the integrity of all contributions.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest related to this report.

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