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Accuracy of Patient-Specific 3D Printed Drill Guides in the Placement of a Canine Coxofemoral Toggle Pin through a Minimally Invasive Approach

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Abstract

Objective The aim of this study was to evaluate the accuracy of patient-specific three-dimensional printed drill guides (3D-PDG) for the placement of a coxofemoral toggle via a minimally invasive approach.

Materials and Methods Pre-procedure computed tomography (CT) data of 19 canine cadaveric hips were used to design a cadaver-specific 3D-PDG that conformed to the proximal femur. Femoral and acetabular bone tunnels were drilled through the 3D-PDG, and a coxofemoral toggle pin was placed. The accuracy of tunnel placement was evaluated with post-procedure CT and gross dissection.

Results Coxofemoral toggle pins were successfully placed in all dogs. Mean exit point translation at the fovea capitis was 2.5 mm (0.2–7.5) when comparing pre- and post-procedure CT scans. Gross dissection revealed the bone tunnel exited the fovea capitis inside (3/19), partially inside (12/19) and outside of (4/19) the ligament of the head of the femur. Placement of the bone tunnel through the acetabulum was inside (16/19), partially inside (1/19) and outside (2/19) of the acetabular fossa. Small 1 to 2 mm articular cartilage fragments were noted in 10 of 19 specimens.

Clinical Significance Three-dimensional printed drill guide designed for coxofemoral toggle pin application is feasible. Errors are attributed to surgical execution and identification of the borders of the fovea capitis on CT data. Future studies should investigate modifications to 3D-PDG design and methods. Three-dimensional printed drill guide for coxofemoral toggle pin placement warrants consideration for use in select clinical cases of traumatic coxofemoral luxation.

Keywords
- coxofemoral luxation
- toggle pin
- dog
- three-dimensional printed drill guide
- minimally invasive

Introduction

Coxofemoral luxation often results from external blunt force trauma and is the most commonly displaced joint in the dog.[1–3] Trauma induces tearing of hip stabilizers, including the joint capsule and the ligament of the femoral head. Luxation of the femur most commonly occurs in a craniodorsal direction, though caudoventral and cranioventral luxations are reported at lower rates.[1–3]

Several methods to reduce the luxation and maintain joint stability have been described.[4] Closed reduction of the hip is often used as a first-line treatment.[4,5] This method is cost-effective and preserves the soft tissue, maximizing biological healing. However, closed reduction results in reluxation rates between 47 and 65%.[1,2] Additionally, in cases of reluxation, definitive treatment with open reduction techniques may be complicated by the additional trauma of repeated joint displacement and the delay in treatment.[4]

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Several surgical options for coxofemoral luxation have been described, including coxofemoral toggle pinning,[3,5,6] triple pelvic osteotomy,[7] femoral head and neck ostectomy,[8] DeVita pinning,[9] total hip replacement[10] and others. Toggle stabilization is one technique that results in high success rates with recent reported reluxation rates between 6 and 11% long-term.[3,6] Typically an open approach to the coxofemoral joint is used to ensure the femoral bone tunnel and suture exit the fovea capitis and enter the adjacent acetabular fossa. Aiming devices have been designed to improve bone tunnel accuracy, but no studies to date have reported the accuracy associated with those devices. Injury to articular cartilage, periarticular soft tissue and neurovascular structures can result in increased pain, morbidity, infection and cost.[11,12] A reliable and minimally invasive approach, which does not involve capsular, tendon or muscle transection, may be beneficial.

Three-dimensional printed drill guides (3D-PDG) have been used in veterinary surgery for fracture repair,[13] angular limb deformities,[14] arthrodesis[15] and spinal surgery.[16] Advantages of 3D-PDG include improved pre-procedure planning, decreased surgical time, decreased complications, decreased intraoperative ionizing radiation exposure, decreased patient discomfort and overall improved surgical accuracy.[17,18]

The aim of this study was to evaluate the feasibility and accuracy of a 3D-PDG for the placement of a toggle pin in the canine coxofemoral joint. We hypothesized that all toggle pins would be successfully deployed via a minimally invasive approach to the proximal lateral femur, with an entry translational error at the third trochanter of < 1 mm, exit translational error at the fovea capitis of < 1 mm and a maximal angle of deviation (MAD) < 1.3 degrees. These values were based on anatomic measurements to ensure the femoral and acetabular bone tunnels exit entirely within the fovea capitis and acetabular fossa respectively.

Materials and Methods

The cadavers of ten dogs that were euthanized for reasons unrelated to this study were used. Breeds included mixed (7/8) and pit bull terrier (1/8). They ranged from 19 to 37 kg body weight and were examined to ensure a healthy appearing and homogenous study population. If a pelvic fracture, proximal femoral fracture or severe coxofemoral crepitus was recognized, the hip was rejected. Median body condition score was 4.5/9 (3.5–8). Cadavers were stored at –20°C and thawed for 72 hours in refrigeration before use. Once thawed, all procedures were performed within 5 days, and cadavers were maintained in refrigeration at 4°C throughout the study.

Pre-procedure Computed Tomography

Pre-procedure pelvic computed tomography (CT) was performed on all specimens. Images were acquired using a 40-slice helical CT scanner (Phillips, Brilliance 40 Slice Medical Systems, Chicago, Illinois, United States) with 0.625 mm slices, a reconstruction overlap of 50%, a field of view large enough to include the circumference of the pelvis including the entirety of the femur bilaterally and reconstructed in a smooth (soft) algorithm. Specimens were positioned in dorsal recumbency with the long axis of the spinal column parallel to the CT table. Pelvic limbs were positioned with both femurs abducted ~20 degrees from sagittal midline and the stifles flexed at ~90 degrees. Volumetric data were stored in digital imaging and communications in medicine (DICOM) format.

Design and Fabrication of Guides

The DICOM files were imported into the Mimics 22.0 software suite (Materialize, Leuven, Belgium). The femur and hemi-pelvises were individually segmented for each specimen using a variety of automatic and manual segmentation techniques. Segmentation masks were converted into 3D models within the Mimics software suite (►**Fig. 1A–C**). Drill trajectories for the path of the toggle stabilization were modelled in Mimics using a combination of the 3D, axial, sagittal and coronal views. A 4 mm cylinder was designed to enter the lateral cortex of the femur distal to the third trochanter and exit the femur at the level of the fovea capitis of the femoral head (►**Fig. 1D**).

The 3D femoral model and drill trajectories were exported to 3-Matic 12.0 (Materialise, Belgium). A portion of the lateral femoral cortex was selected (marked) from the level of the third trochanter and extending 2 to 3 cm distally, including the entry point of the planned trajectory. The selection extended along the cranial surface of the femur at the level of the origin of the vastus lateralis muscle. Caudally the selection extended distally from the level of the lesser trochanter towards the third trochanter. The marked area was offset 2.5 mm externally to form the contact surface and body of the guide. A cylindrical drill sleeve was created around the long axis of the 4 mm cylinder with a radius of 6 mm. The aforementioned parts were merged, and the drill trajectory was subtracted from the guide. Tolerance of the drill tunnel was set to 5%, creating a 4.2 mm drill path (►**Fig. 1E**).

Completed guides were exported as mesh objects in stereolithographic formatted standard tessellation language (STL). The STL files were imported into PreForm, a commercial 3D slicing program (Formlabs, Somerville, Massachusetts, United States) and fabricated in a biocompatible (ISO Standard for Formlabs Vertex-Dental BV resin: EN-ISO 10993–1:2009/AC: 2010, USP Class VI, Utrecht, The Netherlands) and autoclavable photopolymer resin (Form 2 printer, Dental SG resin, Formlabs). Models were washed in 90% isopropyl alcohol for 5 minutes, post ultraviolet light cured at 405 nm for 30 minutes and steam sterilized at 138°C for 3 minutes.[19]

Toggle Placement Using Three-Dimensional Printed Drill Guide

Procedures were performed by a small animal surgical resident and a board-certified surgeon. The specimens were positioned in lateral recumbency with the femur in a neutral standing position and 20 to 30 degrees of abduction.

Based on a previously described minimally invasive approach to the proximal femur,[20] a 4 to 5 cm incision was made centred 1 cm distal to the third trochanter (►**Fig. 2A**). The

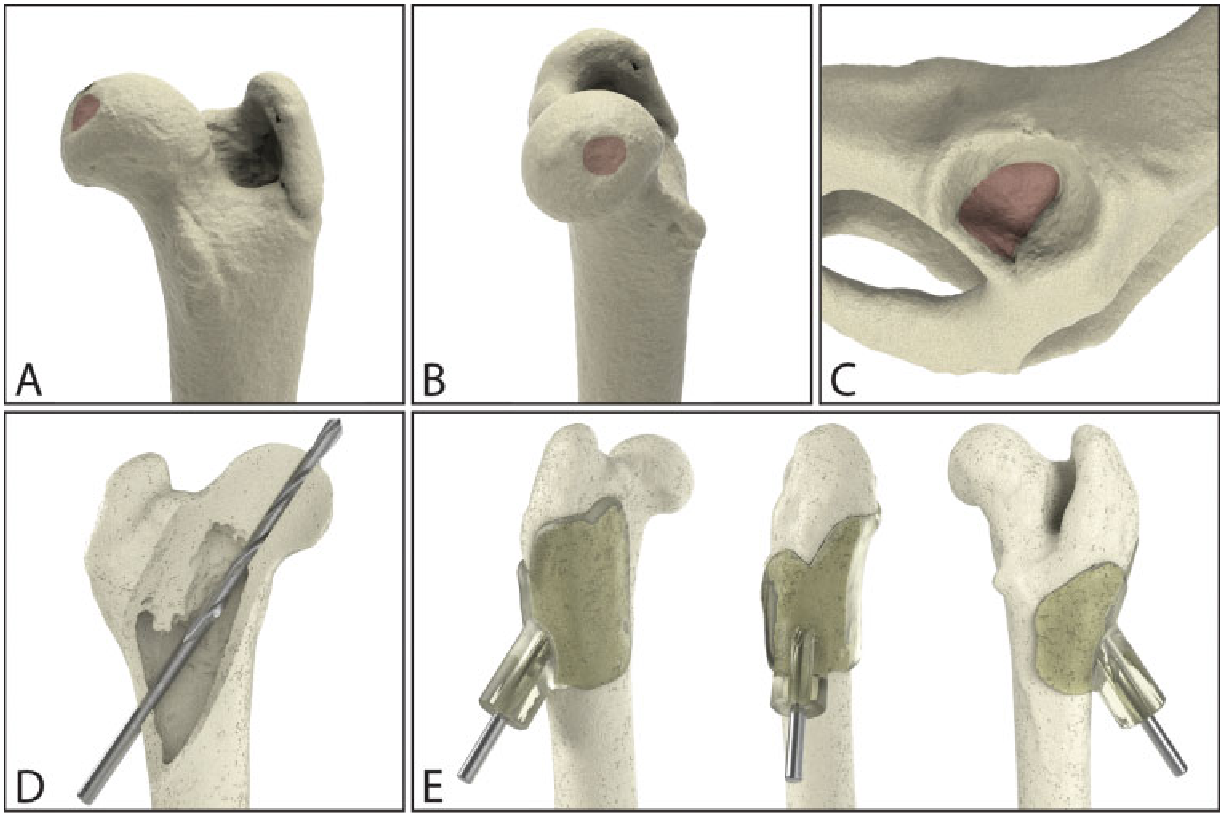

Fig. 1 The fovea capitis is identified by a subtle divot (red) of the subchondral bone of the femur in the three-dimensional reconstruction (**A**, **B**). (**C**) The acetabular fossa (red) is bordered by the transverse acetabular ligament (ventral) and the articular lunate surface of the acetabulum. (D) Three-dimensional reconstruction of the femur with a 4.0 mm drill bit, which enters the lateral cortex of the femur just ventral to the third trochanter and exits through the fovea capitis of the femoral head (B) and the acetabular fossa (**C**). Designed to avoid contact with the endosteal cortex of the femoral neck and trochanteric fossa. (**D**) Completed drill guides applied to the proximal femur in craniolateral, lateral and caudal views (**E**).

tensor fascia was incised cranial to the third trochanter. The biceps femoris muscle was retracted caudally, and the tensor fascia cranially (►**Fig. 2B**) with self-retaining retractors. The caudal border of the vastus lateralis was elevated from the third trochanter and retracted cranially, exposing the cranial and lateral cortex of the femur below the insertion of the superficial gluteal musculature (►**Fig. 2C**). Soft tissue attachments at the bone-3D-PDG contact surface were elevated (►**Fig. 2D**). The 3D-PDG were placed (►**Fig. 2E**) and manually held in position. A 4.0 mm drill bit was used to complete the femoral bone tunnel. The area was lavaged with 0.9% saline, and the drill bit was frequently retracted to remove bone debris from the flutes. A blunted 1.1 mm Kirschner 'feeler' wire was used to probe the acetabular fossa after completion of the femoral bone tunnel to confirm limb positioning prior to drilling the acetabular bone tunnel.

A 2 mm blunted Steinmann pin was placed to maintain tunnel alignment prior to toggle deployment (►**Fig. 2F**). A $3.2 \times 14 \times 1.1$ mm 3D printed polylactic acid replica of a commercially available 3.2 mm toggle pin (IMEX Veterinary Inc, Longview, Texas, United States) threaded with 27 kg nylon monofilament suture was passed using the Steinmann pin through the femoral and acetabular tunnel. The suture was retracted with the Steinmann initially in place, then seated firmly against the medial wall of the acetabulum following removal (►**Fig. 2G**). Once secure, the suture was tied over a polylactic acid button with four throws to maintain mild lateral compression.

Post-procedure Assessment

A post-procedure CT was performed to assess the accuracy of bone tunnels from the intended entrance, exit and trajectory. Post-procedure DICOM files were imported into Mimics 22. Three-dimensional models of each femur were segmented as previously described. Planned and post-procedure femoral models were exported to 3-Matic. Planned femoral models were shape matched to the corresponding post-procedure femoral model using the global positioning function. A part comparison analysis confirmed the accuracy of cortical shape matching to < 0.5 mm in areas where segmentation error would be minimized (diaphysis, distal femur) (►**Fig. 3**). Models were imported into Mimics 22. Multiplanar reconstruction was performed to define the x, y and z axis. Planes for the x- and y-axis bisected the centreline of a best fit 4.0 mm cylinder, matched to the post-procedure bone tunnel (►**Fig. 4A**). Quantitative comparisons of planned and post-procedure bone tunnels were evaluated at the level of the entrance near the third trochanter (►**Fig. 4C–E**) and the exit at the fovea capitis (►**Fig. 4B–E**). The centre to centre translation of the entrance at the third trochanter (CT-TRANS-3T) and exit at the fovea capitis (CT-TRANS-FC), and the direction of translation for both the entrance (CT-DIR-3T) and exit (CT-DIR-FC), were measured

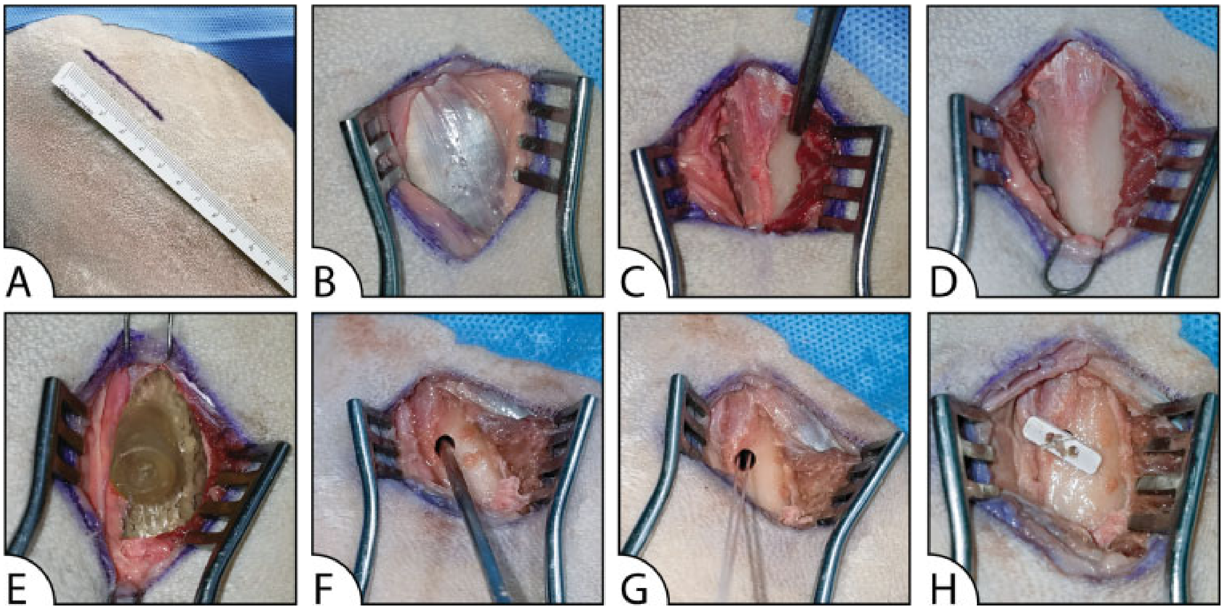

Fig. 2 (**A**) A 4–5 cm incision was made directly over the proximal femur, centred 1 cm distal to the third trochanter. (**B**) Tensor fascia transected from cranial edge of biceps femoris and retracted cranially (tensor fascia) and caudally (biceps femoris). (**C**) The vastus lateralis was elevated from the third trochanter cranially, leaving the proximal origin attached. (**D**) Elevation of soft tissue distal to the ridge of the third trochanter, extending to the muscle origin. (**E**) Three-dimensional printed drill guides applied to the lateral femoral cortex with the limb abducted 20 to 30 degrees. (**F**) A blunted Steinmann pin (2 mm) was used to maintain alignment of the femoral and acetabular bone tunnels prior to toggle placement. (**G**) Nylon suture exiting the lateral femoral bone tunnel following placement. (**H**) Secured three-dimensional printed two-hole button along the lateral femoral cortex.

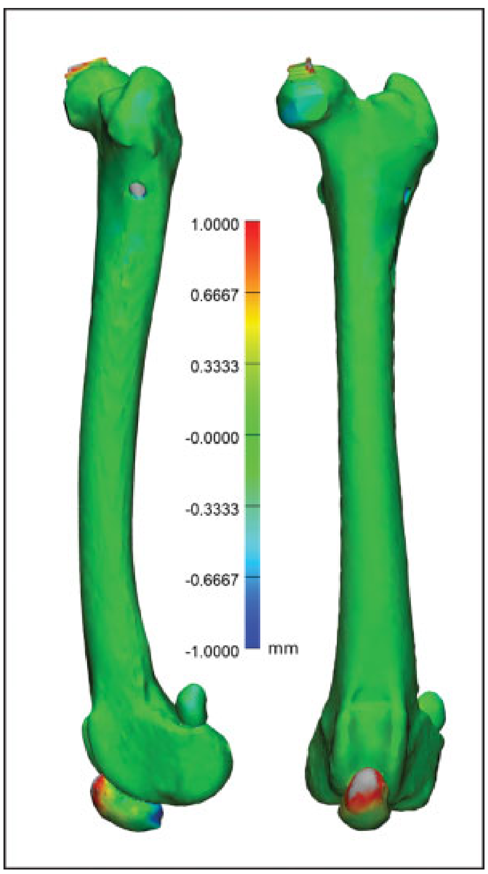

Fig. 3 Part comparison of shape matching accuracy for planned and post-procedure femoral models. Anatomy less susceptible to segmentation error (cortical diaphysis) was matched to an accuracy of < 0.3 mm (green).

directly in the software (►**Fig. 4B–E**). The MAD between the pre-planned cylinder and post-procedure bone tunnel in x and y planes was measured from centreline to centreline directly in the software.

Following a post-procedure CT scan, the coxofemoral joints were evaluated grossly for placement, articular damage and bone debris. Results were classified as inside, partial or outside. A designation of inside described an exit hole that lies completely within the ligament of the head of the femur or acetabular fossa without disturbance of articular cartilage. A designation of partial described the partial disruption of articular cartilage surrounding the ligament of the head of the femur or lunate surface of the acetabulum. Failure to exit the femoral head with no contact with the ligament of the head of the femur or failure to enter the acetabulum no contact to the acetabular fossa was considered outside. The difference between the centre of the ligament of the head of the femur and exit at the fovea capitis was measured using digital calipers and is referred to as the gross dissection exit translation (G-TRANS-FC).

Statistical Analysis

A pre-experimental power analysis was performed, based on an estimated accuracy of 2 mm of intended placement at each point observed (third trochanter and fovea capitis). As one animal will have two hips analysed, each animal was considered a block factor in a randomized block design model. With an estimated standard deviation (SD) of 50%, five animals were required to achieve a power of >80%. Thus, 10 cadavers were considered adequate to demonstrate the techniques feasibility with power >99%. Statistical analyses

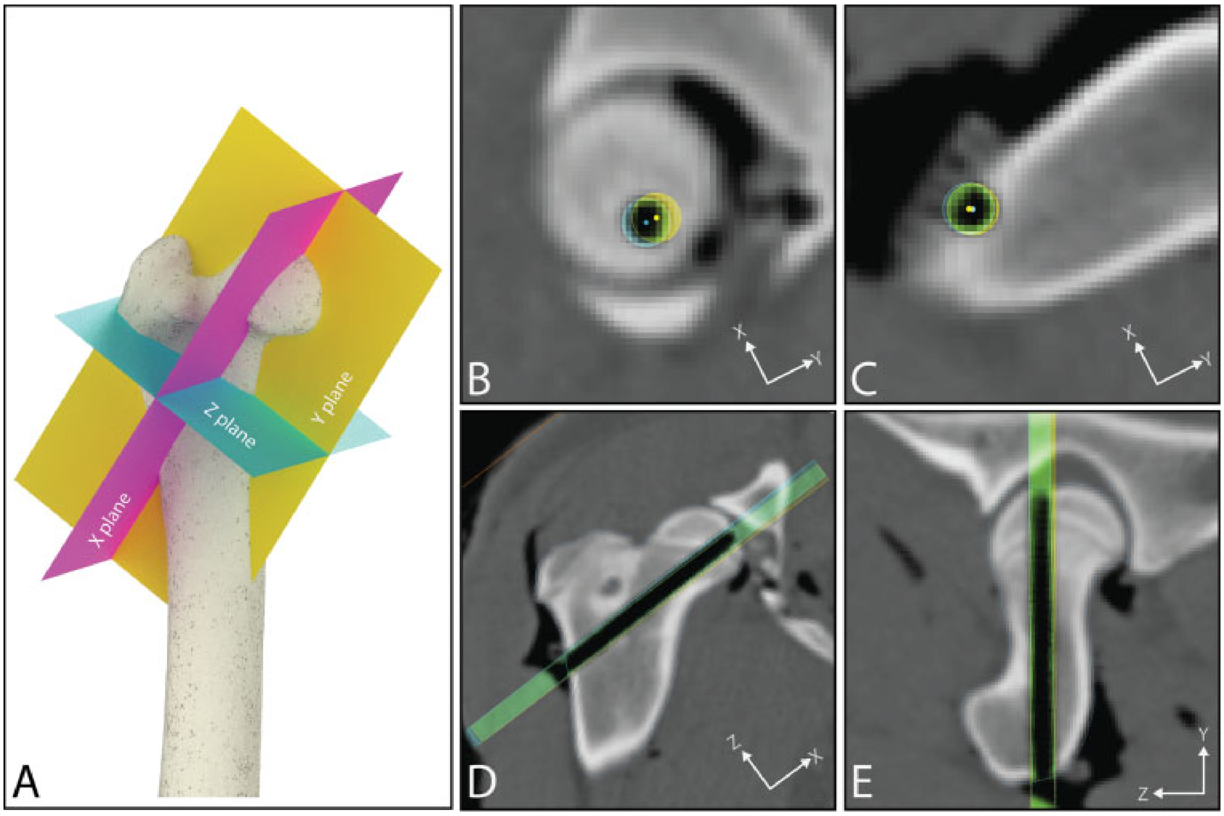

Fig. 4 (**A**) Coordinate system for comparison analysis of planned and post-procedure bone tunnels. The post-procedure bone tunnel was bisected by x and y planes. (**B**) Direct measurement of the centre to centre translation in post-procedure specimens at the fovea capitis. (**C**) Direct measurement of the centre to centre translation in post-procedure specimens at the level of the third trochanter. (**D**) Sagittal view of planned (yellow) and post-procedure (blue) bone tunnels used to directly measure the maximum angle of deviation in the y plane. (**E**) Coronal view of planned (yellow) and post-procedure (blue) bone tunnels used to directly measure the maximum angle of deviation in the x plane.

were conducted using SAS for Windows version 9.4 (SAS Institute, Cary, North Carolina, United States).

Results

Nineteen hip joints from ten cadavers were evaluated. One hip was excluded as a result of a proximal diaphyseal femoral fracture.

Mean incision length was 4.7 cm (3.6–6.9). Mean approach time was 9 minutes (8.75–9.5 minutes) and time to toggle placement was 8.1 minutes (6.25–10 minutes). All toggle pins were placed successfully through the femoral bone tunnel, without early deployment within the joint.

Post-procedure CT revealed a mean CT-TRANS-3T of 1.1 mm (SD: 1.2 mm, range: 0–5.3 mm). The CT-DIR-3T was proximal (5/19), cranial (2/19), distal (7/19), distocaudal (1/19) and caudal (3/19) directions (►**Fig. 5A**). No translation was observed in one specimen. The mean CT-TRANS-FC of the bone tunnel was 2.5 mm (SD: 2.0, range: 0.19–7.5 mm). The CT-DIR-FC was proximal (4/19), distal (4/19), distocaudal (3/19), caudal (6/19) and proximocaudal (2/19) (►**Fig. 5B**). The mean MAD was 2.2 degrees (SD: 2.1 degrees, range: 0.07–6.4). Post-procedure cadaveric gross dissection revealed placement through the fovea capitis was inside in 3/19, partial in 12/19 and outside in 4/19 specimens (►**Fig. 6A–C**). The mean CT-TRANS-FC was 3.3 mm (1.0–6.3 mm). Excluding inside placement, the G-DIR-FC was proximal (2/16), distocaudal (8/16), distal (1/16) and caudal (5/16).

Placement of the bone tunnel through the acetabular fossa was considered inside (16/19), partial (1/19) and outside (2/19) (►**Fig. 6D–F**). Ventral deviation in acetabular fossa placement caused damage to the ventral transverse ligament of the acetabulum ($n = 2$). Small intraarticular debris was found in 10/19 specimens and consisted of thin (~1 mm) pieces of articular cartilage lifted from the rim surrounding the fovea capitis with a mean diameter of 3.3 mm (0.5–6.2 mm) in the largest dimension. No signs of cartilage damage were detected as a result of the 2 mm blunt Steinmann pin or 1.1 mm blunted Kirschner wire.

Discussion

The hypothesis that all toggles would be successfully deployed via a minimally invasive approach was accepted. The hypothesis that 3D-PDG would permit a femoral drill tunnel with CT-TRANS-3T < 1 mm, CT-TRANS-FC and G-TRANS-FC < 1 mm and MAD < 1.3 degrees are rejected.

Guidelines for determining the success of the methods were derived from previous literature[5] and applying similar methods to relevant femoral anatomy. Serdy and collegues[5] based the success of their fluoroscopically guided toggle pin

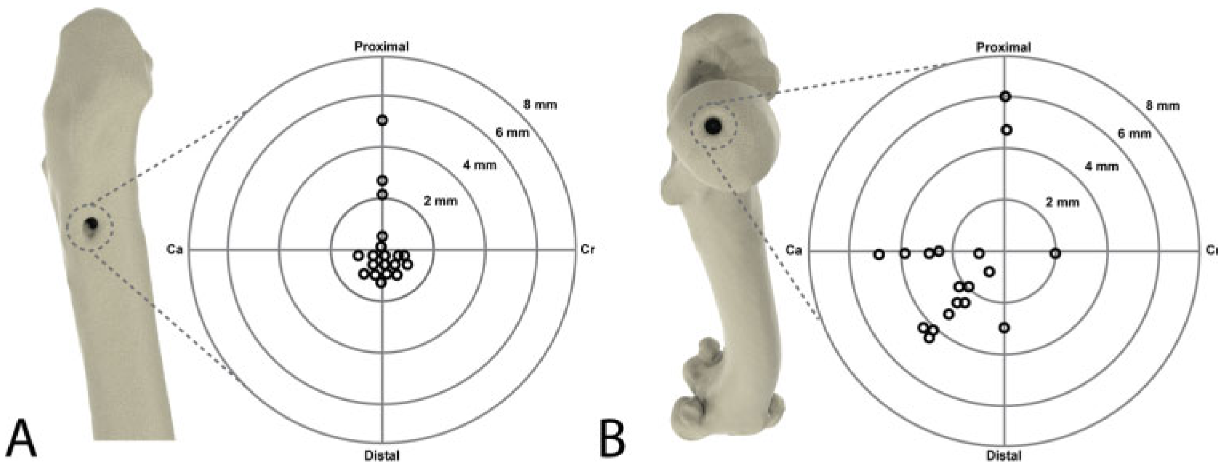

Fig. 5 (**A**) Direction and magnitude of femoral entry point translation at the lateral femoral cortex relative to planned femoral entrance points (centre). (**B**) Direction and magnitude of femoral exit point translation at the fovea capitis relative to the planned exit point (centre).

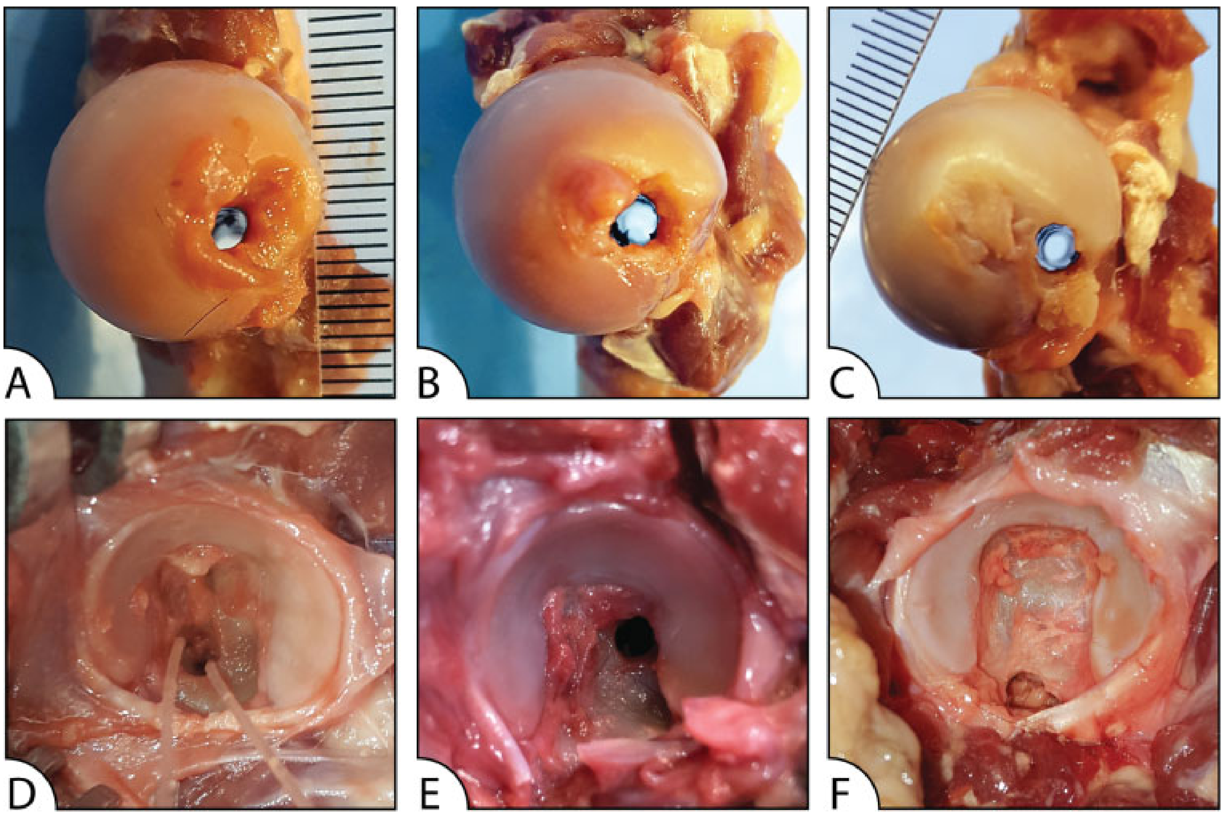

Fig. 6 Cadaver dissections representing inside (**A**), partial (**B**) and outside (**C**) placement of the bone tunnel relative to the fovea capitis. Inside (**D**), partial (**E**) and outside (**F**) placement of the bone tunnel relative to the acetabular fossa.

placement on gross dissection and defined ideal placement as a drill hole in contact with fovea capitis. Using those guidelines, 15 of 19 specimens in our study would be defined as inside or ideal. To more objectively quantify error, several studies in human[17,18,20–24] and veterinary surgery[16] have used grades of error (in intervals of 2 mm) based on executed tunnel trajectories seen on post-procedure versus planned trajectories. These other studies have been performed on cervical pedicle screw placement, which have vastly different requirements than the hip joint. In our population of dogs, the non-articular fovea capitis at the insertion of the ligament of the head of the femur was $\sim$ 5.8 mm (range: 4.7–7.8 mm) in diameter at gross dissection. The difference between the radius of the fovea capitis ($\sim$3 mm) and the radius of the drill bit (2.0 mm) is $\sim$1 mm. Thus, a translation $>$1 mm would result in a femoral drill tunnel that likely would contact articular cartilage. With a femoral tunnel length of $\sim$4.5 cm, this corresponds to a MAD of 1.3 degrees. Thus, a CT-TRANS-3T and CT-TRANS-FC to $<$ 1 mm, and MAD $<$ 1.3 degrees, rather than a standard 2 mm tiered grading scheme were chosen for this study. The amount of error tolerated in a clinical setting is unknown.

The two methods used to evaluate accuracy (gross inspection and analytical CT comparison) allowed the authors to speculate on sources of error. Guide construction (CT acquisition parameters, design and 3D printing) and intraoperative factors (soft tissue elevation, guide application, drill bit walking, or deflection) are represented by differences in planned and executed drill tunnels: CT-TRANS-3T (1.1 mm) and CT-TRANS-FC (2.5 mm). Stereolithography 3D printers have proven capable to print with 1% error,[25] indicating that intraoperative error was a more likely source of error in the study. The guides were sterilized as would be done clinically to account for possible morphological changes that may occur in the process. Polylactic acid toggles were chosen to avoid beam hardening artifact and minimize analytical error in the post-procedure CT. To minimize intraoperative errors, complete elevation of soft tissues is crucial to allow optimal contact between the 3D-PDG and cortical bone. Non-axial pressure applied to the 3D-PDG during drilling may alter the MAD and should be avoided.

On gross dissection, mean G-TRANS-FC was 3.3 mm compared with a mean CT-TRANS-FC of 2.5 mm; a difference of 0.8 mm (0.12–2.73 mm) between the two methods of evaluation. This represents additional error beyond intraoperative execution. This planning error is thought to arise from difficulty in accurately identifying the true centre of the fovea capitis on CT images. Magnetic resonance imaging or CT arthrography may provide additional information to help alleviate this source of error. Additionally, shape matching of planned and post-procedure models is susceptible to differences in CT acquisition, artifact and segmentation error. A part analysis in each specimen revealed accuracy to < 0.3 mm (►**Fig. 4**).

A 4.0 mm drill bit was used to accommodate the 3.2 mm toggle pin and nylon suture. Clinically a 3.5 mm drill bit may be preferential for a 3.2 mm toggle pin, when used with alternative suture materials, such as Fibertape (Arthrex Vet Systems, Naples, Florida, United States). Stronger materials may be preferential in clinical cases where a capsulorrhaphy is not able to be performed.

Acetabular bone tunnels were located inside or partial in 17/19 joints. A femoral abduction angle of 20 to 30 degrees (15–45 degrees) with neutral femoral rotation was acceptable based on simulated surgical planning. An error ventral to the acetabular fossa (2/19) can be explained by a femoral abduction angle that was too steep or a femoral bone tunnel that exited ventral to the fovea capitis. In specimens with outside acetabular placement ($n = 2$), the G-TRANS-FC was caudodistal. Over abduction of the limb was suspected on subsequent re-evaluation of gross specimens. Acetabular lunate surface cartilage damage has been previously reported in 6/16 joints when drilling through the femoral tunnel in a closed reduction method.[26] This is a slightly higher rate than reported here. The blunted Kirschner wire was helpful and straightforward in determining the differences between the lunate surface and acetabular fossa, and may be one reason for the improved acetabular tunnel placement.[26] In clinical cases, torn remnants of the joint capsule could cause difficulty in accurately identifying the acetabular fossa. In those instances, extending the surgical approach to the coxofemoral joint is necessary.

In comparison to the first 12 procedures, the final seven outcomes improved in mean G-TRANS-FC distance by 9% (3.1 from 3.4 mm), percentage of inside fovea placement (8.3 to 29%), partial fovea placement (58 to 71%) and outside fovea placements (33 to 0%). Mean CT-TRANS-FC also improved by 32% (2.8 to 1.9 mm). Reduction in the femoral abduction to 20 degrees in the final seven specimens, combined with experience, resolved inadequate acetabular placement (17 to 0%).

Minimally invasive approaches have advantages including reduced cost, pain, morbidity and potential for decreased infection,[11,12] though they often require an alternate form of surgical guidance. In this study, CT data and a 3D-PDG were used for a minimally invasive coxofemoral toggle pin. Additional methods include intraoperative fluoroscopy, or arthroscopy to assist in accurate implant placement.[5,18] One report of minimally invasive hip toggle in 14 cadaver hip joints and two clinical reports describe the use intraoperative fluoroscopy.[5] This technique was successful (considered inside or partial in the guidelines for this study) in 60% of cadavers, and improved to 75% with a modification of their technique (guide wire, cannulated drill bit). However, the procedure was aborted in 25% of procedures as a result of guide wire bending and shearing within the coxofemoral joint.[5] The overall cost for this procedure is dependent on the costs associated with a CT scan and 3D planning, which can vary significantly based on the software and 3D printer.

The minimally invasive approach described here does not entail treatment or evaluation of the coxofemoral joint. Combining the procedure with arthroscopic evaluation of coxofemoral joint would allow for more complete assessment of articular surfaces. Small fragments of articular cartilage were observed in the coxofemoral joint in 10/19 specimens on gross dissection. Fragments were the result of avulsion of the articular cartilage attached to the remaining ligament of the head of the femur, and were not apparent on post-procedure CT. Cartilage avulsion may in part be explained by the freeze–thaw cycle, which has been shown to weaken articular cartilage.[27,28] If osseous debris is noted on preoperative imaging, or irreducible tissue entrapment is suspected or confirmed intraoperatively, an open approach is indicated.

Limitations to this study include using cadavers without coxofemoral luxation. Pre-existing osteoarthritis of the coxofemoral joint was reported in 13/62 (23%) of dogs that received an open reduction hip toggle,[3] though it had no effect on outcome of the procedure. Skeletal variations exist between dogs[29] and variation in conformation was not assessed in this study. However, 3D-PDG are designed to identify the ideal femoral to acetabular tunnel in each animal, regardless of conformation. Finally, this study did not compare 3D-PDG to a prospective cohort using other methods for completing a transfemoral tunnel. No studies to date have reported the accuracy of open methods of a coxofemoral toggle pin.

In conclusion, femoral 3D-PDG were successfully used to place toggle pins in normal canine cadavers. While the results of this study are promising, small sources of error prevented accurate placement in all specimens. Post-hoc analysis suggests that there is a short learning curve when beginning to use PDG. Ultimately, the amount of error tolerated in a clinical setting, in both the short and long-term, is unknown. Future studies should involve continued modifications to 3D-PDG design, materials and methods. This study warrants further investigation into the use of 3D-PDG in select clinical cases of traumatic coxofemoral luxation in dogs.

Authors' Contributions

B.G.D. and K.A.S. designed the experiment and collected the results. All authors discussed the results and analyzed the data. B.G.D. and K.A.S. wrote the manuscript. K.A.S. created the illustrations.

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Conflict of Interest

None declared.

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