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EXPERIMENTAL LAB RESEARCH

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Computer-assisted surgery for placing toggle constructs across the coxofemoral joints of small equids using a minimally invasive approach–A proof-of-concept cadaveric study

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Abstract

Objective: To develop a minimally invasive technique for placing a toggle construct across the coxofemoral joint of small equids using computer-assisted surgery.

Study design: Experimental cadaveric study.

Sample population: Three pilot specimens: One donkey, one Shetland pony and one Warmblood foal. Six main study specimens: Three Shetland ponies, one American Miniature Horse, one Warmblood foal and one donkey.

Methods: Experimental surgeries were performed on both coxofemoral joints of each cadaver. Using a minimally invasive surgical approach, 5.5 mm bone canals were drilled through the femur and acetabulum, traversing the coxofemoral joint. Intraoperative guidance was provided by a cone-beam computed tomography (CBCT)-coupled surgical navigation system. A toggle construct was introduced through the bone canals. Surgical accuracy aberrations (SAA) were measured at the femoral entry and exit points and at the acetabular entry point on merged pre- and postoperative CBCT scans. The coxofemoral joint was assessed for articular cartilage damage by gross dissection.

Results: A toggle construct was placed across all 18 coxofemoral joints. The overall median SAA in the main study was 2.8 mm (range: 0.4–8.0 mm). No cartilage damage was found in the cadaveric specimens of the main study.

Conclusion: The described technique allowed for the placement of a toggle construct across the coxofemoral joint of small equid cadaveric specimens without prior coxofemoral luxation.

Clinical relevance: This technique may serve as an option for surgical stabilization of coxofemoral joints in small equids. Further biomechanical investigations are required to assess optimal implant positioning and toggle constructs.

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1 | INTRODUCTION

Coxofemoral luxation is a rarely reported condition in equids, occurring most commonly in young horses, ponies and miniature breeds.[1] Reported causes are direct trauma, including falls, kicks, struggling to extract an entrapped limb,[2] as a complication of wearing a full limb cast,[3] or as a consequence of upward fixation of the patella.[4] The clinical diagnosis is based on the findings of the orthopedic examination, confirmed by radiography or ultrasonography.[5,6] In equids, the direction of luxation of the femoral head from the coxofemoral joint is reported to be most commonly craniodorsal.[1,2]

In small equids, closed reduction of the luxation with subsequent restriction in movement (application of an Ehmer sling, or restraint in a rescue sling, usually combined with prolonged confinement in a box stall) can be successful.[1,7,8] However, re-luxation appears to be common, and open reduction combined with some form of surgical stabilization is frequently advocated.[1,2] Techniques for extra-articular stabilization have been described, including a prosthetic capsule technique[9] and a synthetic capsular reconstruction, with or without transposition of the greater trochanter.[10] Techniques that combine extra-articular stabilization with a toggle construct to provide additional stability have been described.[10,11] Unfortunately, regardless of the surgical technique, failure of fixation following successful open reduction and surgical stabilization appears to be common.[2] Repeating the placement of the toggle construct with extra-capsular stabilization, femoral head ostectomy[12] or total hip arthroplasty[13,14] are the options to salvage an affected small equid. The costs and postoperative complications associated with these procedures are considerable. Although retrospective analyses describing prognosis and outcome are lacking, it is generally agreed that treatment of coxofemoral luxation in equids is challenging.[13]

Multiple studies in dogs and a single case report in an Alpaca describe successful stabilization of coxofemoral luxations by the exclusive use of toggle constructs after an open reduction.[15–17] Moreover, in dogs, minimally invasive toggle pinning techniques following closed reduction of coxofemoral luxation are being developed[18–20] and their use has been reported in two cases.[19,21] As all previously described techniques for surgical stabilization of the coxofemoral joint in small equids require an open approach to the joint, this inevitably requires capsular, tendon or muscle transection. In order to avoid the morbidity associated with an open approach to the coxofemoral joint, a minimally invasive approach for coxofemoral joint stabilization, similar to that developed in dogs, could be a potentially useful addition to the currently available treatment options in small equids.

In the early 2000s, mobile cone beam computed tomography (CBCT) units that can be coupled with a surgical navigation system became available for computer-assisted surgery (CAS). Computer-assisted surgery can provide real-time intraoperative image-guidance for surgical procedures requiring optimal intraoperative orientation, thus facilitating minimally invasive approaches. This technology has been introduced for orthopedic interventions in equine surgery.[22–25] If equipped with a large bore gantry, CBCT imaging units can readily accommodate the pelvis of small equids. Most surgical navigation systems currently used for orthopedic surgery have an integrated optical tracking system. These systems use an infrared camera to ascertain the position of tracking devices on the targeted bone, often referred to as patient trackers, and on the navigated instruments, so-called instrument trackers. A navigation software then correlates the position of the tracked surgical instruments in spatial relation to the previously gathered medical imaging data set of the anatomical region of interest. However, when applying optical tracking systems, it is important that the patient tracker is anchored in a fixed position and in an angle-stable orientation relative to the anatomy of interest.[26,27] We speculated that this technology could provide the intra-operative guidance necessary in a minimally invasive procedure for surgical stabilization of the coxofemoral joint in small equids.

The aim of this proof-of-concept study was to develop a CAS technique for placing a toggle construct across the coxofemoral joint in small equids and evaluate the accuracy of the drilling procedure. Specifically, a CAS setup was tested, where the patient tracker is anchored to the tuber coxae, and the coxofemoral region is stabilized with the help of a calf jack for the duration of preoperative imaging and the surgical procedure.

We hypothesized that this arrangement would:

1. Allow for accurate navigated drilling of aligned 5.5 mm bone canals through the femur and acetabulum, such that the level of surgical accuracy achieved would avoid detectable iatrogenic articular cartilage damage to the coxofemoral joint.
2. Permit a toggle construct to be reliably placed across the coxofemoral joint via the drilled bone canals.

2 | MATERIALS AND METHODS

Nine cadaveric specimens of client-owned equids, without known underlying orthopedic conditions, euthanatized for reasons unrelated to the study, were collected.

TABLE 1 Signalment of the cadaveric specimens.

Cadaveric specimen	Breed	Age	Bodyweight
Donkey 1	Miniature donkey	20 years	182 kg
Pony 1*	Shetland pony	30 years	148 kg
Foal 1*	Warmblood	4 months	164 kg
Donkey 2	Miniature donkey	19 years	152 kg
Pony 2	American miniature horse	12 years	95 kg
Pony 3	Shetland pony	16 years	106 kg
Pony 4	Shetland pony	25 years	143 kg
Pony 5	Shetland pony	22 years	161 kg
Foal 2	Warmblood	5 months	190 kg

Note: The 3 cadaver specimens shown in gray font were used for pilot trials.
*The whole cadaver was frozen and used for the experiment.

Appropriate methods of euthanasia, according to AVMA guidelines for the euthanasia of animals, were followed. Cadavers were donated after owners had signed an informed consent form, permitting the use of tissues and images for research purposes. The first three cadavers (i.e., 6 nonluxated coxofemoral joints) were used for pilot trials, which served to refine and standardize the complex surgical planning of the CAS technique. Following the initial phase of pilot trials, six cadavers (i.e., 12 nonluxated coxofemoral joints) were included in the main study. On all nine cadavers, the surgical technique was performed bilaterally. Because of limited freezer capacity, seven cadavers were eviscerated, sectioned in half at the level of the lumbosacral junction and stored at −20°C (Table 1).

2.1 | Preparation of cadaveric specimens and positioning for imaging and surgery

The pilot and study cadaveric specimens had the same preparation. The specimens were thawed at room temperature for 72–96 h prior to the experiments. The hair over the croup, lateral aspect of the coxofemoral articulation and proximal femur was clipped. Each specimen was then placed in lateral recumbency, with the palpable greater trochanter centered between the long edges of the carbon fiber table (Opera Swing, General Medicale Merate SPA, Seriate, Italy) and the long axis of the spine oriented parallel to the long axis of the table. The limbs were positioned so that the joint angulation resembled that of their neutral standing position. Care was taken to avoid inducing any ab- or adduction or correcting any pre-existing outward rotation of the limb. The horizontal bar of a calf jack was placed sagittally between the thighs of the specimen so that the pole of the jack was aligned parallel to the long axis of the pelvic extremities (Figure 1). A rope was then looped around the distal crus of the upper limb and connected to the ratchet of the jack. The ratchet mechanism of the calf jack was then tightened in order to apply moderate traction to the limb. The pole of the jack was then taped to a tripod (Figure 1A–C). The patient tracker (passive orthopedic reference frame 963–864 and fixator 9730864, StealthStation System, Medtronic, Louisville, Colorado) was fixed to the dorsolateral aspect of the upper tuber coxae using two 3.2 mm self-tapping Schanz pins. The pins were inserted via stab incisions and the patient tracker was oriented so that the reflecting spheres were facing towards the infrared camera of the optical tracking system (Figure 1).

2.2 | Preoperative image acquisition

A mobile CBCT unit (O-arm Imaging System, Medtronic) coupled with a surgical navigation system (StealthStationS7; Medtronic) provided pre- and postoperative imaging for all experimental surgeries, including the pilot trials. The gantry of the CBCT was centered on the greater trochanter of the upper limb. This required an approximately caudo-70°dorsal-cranioventral oblique orientation of the gantry relative to the long axis of the carbon fiber table, to avoid interference with the pelvic extremities (Figure 1A,B). Adequate positioning of the coxofemoral region in the center of the gantry was confirmed with two orthogonal projections, using the integrated fluoroscopy function of the imaging unit. Prior to running the preoperative scan, it was ensured that the localizer camera of the optical tracking of the navigation system simultaneously detected the reflecting spheres of the patient tracker and the infrared light-emitting tracker of the gantry (Figure 1). A high-definition volumetric scan was acquired using 120 kV and an exposure of 125 mA.

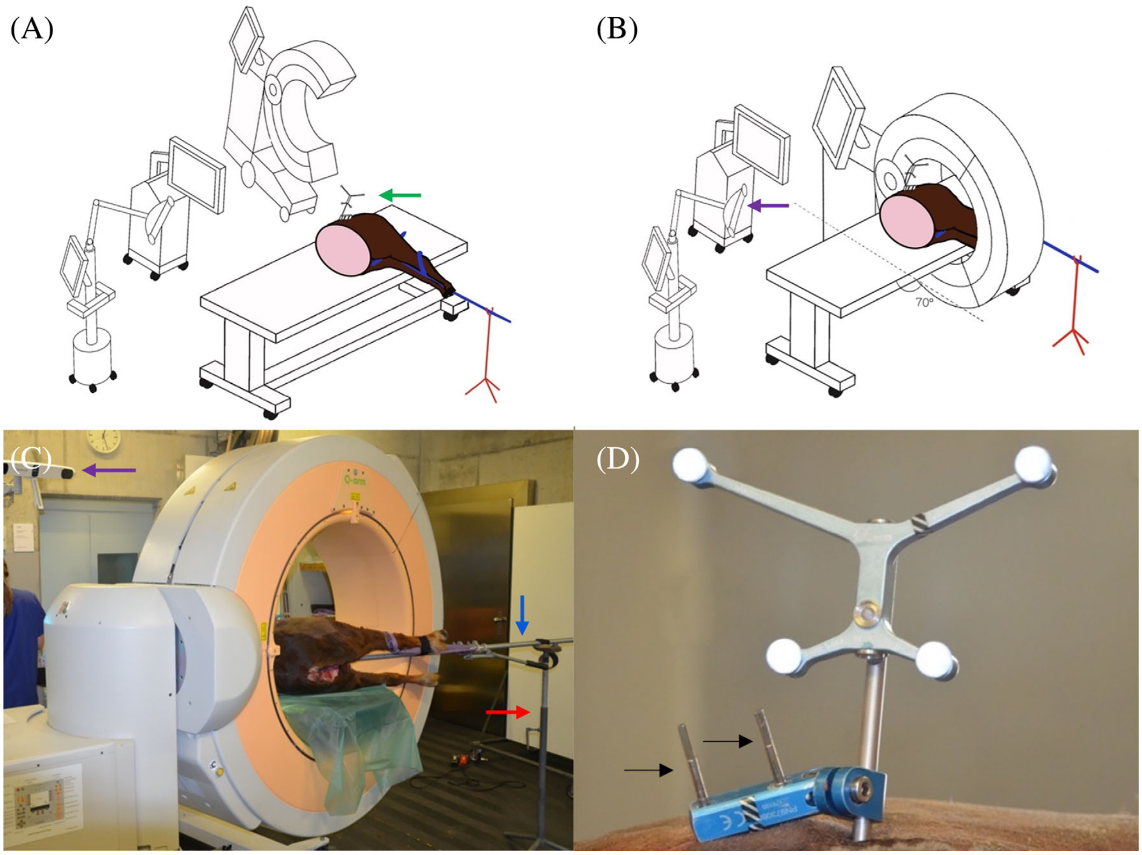

FIGURE 1 Preparation and positioning of a cadaveric specimen for preoperative imaging and surgery of the left limb. The cadaveric specimen is positioned in lateral recumbency on a carbon fiber table, with the limb of interest uppermost. The horizontal bar of a calf jack was placed between the thighs. The pole of the calf jack (A, B: in blue, C: blue arrow) was placed on a tripod (A, B: in red; C: red arrow) and taped in position to stabilize the extremity. The patient tracker (A: green arrow; D: showing close-up) was fixed to the dorsolateral aspect of the upper tuber coxae and oriented so that the reflecting spheres were facing cranial towards the infrared camera of the optical tracking system (B: purple arrow). (A, B) Technical illustration of the cone-beam computed tomography setup. The gantry is positioned in an approximately caudo-70°dorsal-cranioventral oblique orientation relative to the long axis of the table, as indicated by the dashed line. This helps avoid interference between gantry and the pelvic limbs and the calf jack. (C, D) Photographs depicting the cone-beam computed tomography (CBCT) setup in an experimental surgery of a right limb. In (C), a caudodorsal perspective of the CBCT setup is shown, and (D) provides a close-up view of the patient tracker, anchored to the tuber coxae with two 3.2 mm self-tapping Schanz pins (black arrows).

During an acquisition time of 27 s, 745 projections were made in a single tube rotation and reconstructed into 192 transverse isotropic images, which were automatically exported from the CBCT to the navigation system.

The CBCT images of the femur and acetabulum were displayed as multiplanar reconstructions in the dorsal and transverse planes (but annotated "coronal" and "axial," respectively), as well as a 3D volumetric reconstruction on the monitor of the navigation system. These were then inspected by a board-certified Diplomate in veterinary diagnostic imaging (EVdV). The imaging data set was considered as being of adequate quality if it allowed for the identification of the anatomical landmarks needed for surgical planning. Specifically, the proximolateral aspect of the femur, the femoral head, and the medial contour of the acetabulum needed to be completely included. The gantry was opened and the CBCT imaging unit was removed from the surgical field.

2.3 | Surgical planning

The Cranial Software (Medtronic, Louisville, Colorado) of the navigation system was used for surgical planning. All investigators participated in the surgical planning of the first procedures and in developing the standardized surgical plan. The surgical planning of the pilot specimens differed from that of the study specimens in that it lacked a standardized selection and arrangement of reconstructed CBCT images used for the planning as well as a final verification step. Patient registration was

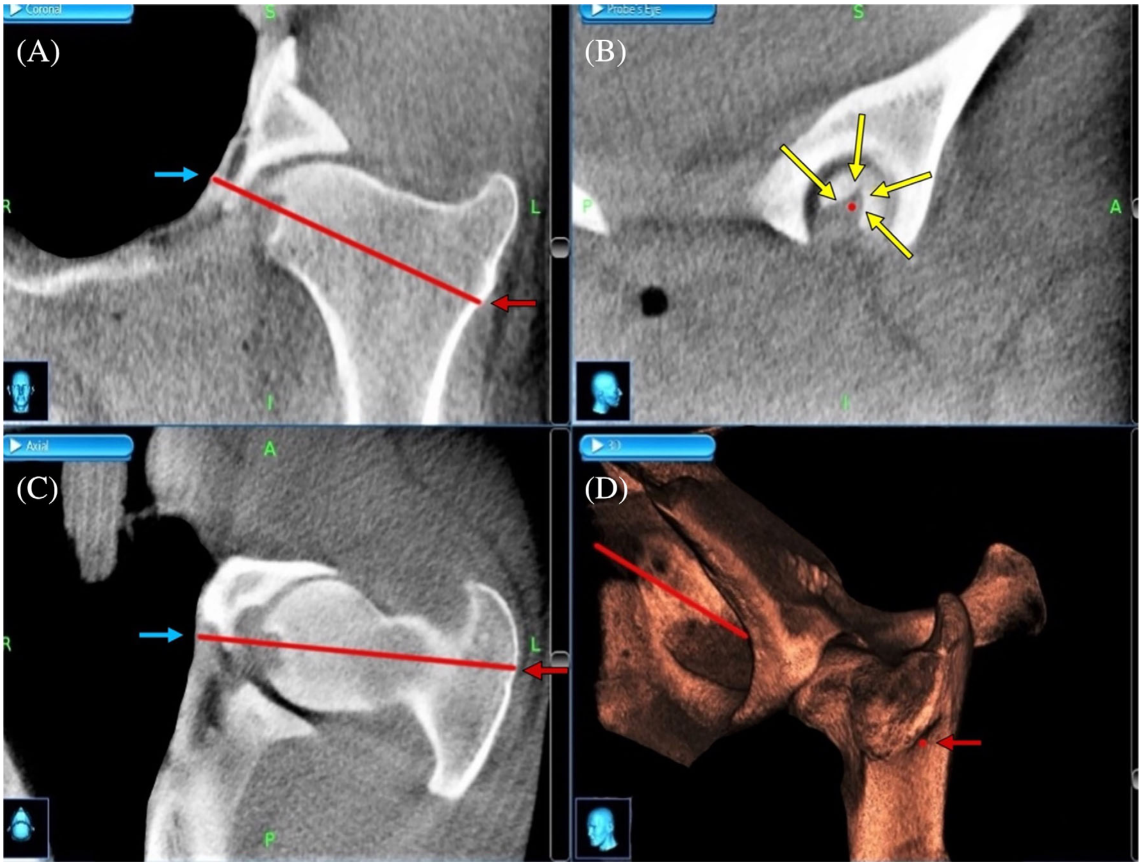

FIGURE 2 Screenshot of the cone beam computed tomographic images used for preoperative planning of Pony 2. Depicted are: A dorsal multiplanar reconstruction of the femur (annotated "coronal") (A), a probe's eye view (B), and a transverse multiplanar reconstruction (annotated "axial") (C), as well as a 3D volumetric reconstruction (D). The finished surgical plan is shown as a red line or red dot, respectively, representing the core axis of the planned drill corridor. The entry point into the lateral femur (A, C, D: red arrow), the triangular fovea capitis of the femur (B: yellow arrows) and the exit point through the medial cortex of the craniodorsal part of the acetabulum (A, C: blue arrows) are illustrated. The axis of the planned drill corridor is centered within the contours of the femoral neck in all multiplanar reconstructions.

performed by placing the tip of the navigated pointer (Passive Planar Probe [sharp], 960–553, StealthStation System, Medtronic) in the divot of the patient tracker. Two planar reconstructions, trajectory 1 and 2, and two 3D volumetric reconstructions of femur and acetabulum were chosen for display on the navigation monitor (Video S1). The trajectory views (trajectory 1 and 2) are reconstructed image planes oriented perpendicular to each other, intersecting in the long axis of the shaft of the navigated pointer or instrument, respectively, and its projection. These help to position the tip of the navigated pointer or instrument at the desired entry site and subsequently align the instrument shaft with the envisioned or previously planned trajectory. One of the 3D reconstructions was oriented to show the lateral aspect of the femur, that is, the area where the anticipated entry point of the drill corridor is situated. The other 3D reconstruction was oriented to show the medial aspect of the acetabulum, the area of the anticipated exit point of the drill corridor (Video S1).

To produce a preliminary surgical plan, the "navigate instrument" function was selected on the navigation monitor and a virtual projection of 10–15 cm length was implemented for the navigated pointer. The operating surgeon then palpated the greater trochanter and positioned the tip of the navigated pointer approximately 2–3 cm distally. Using the views displayed on the navigation monitor, the surgeon aimed to make the entry point into the smooth-surfaced proximolateral shaft of the femur, approximately 2–3 cm distal to the palpable cranial part of the greater trochanter, centered between the cranial and caudal border of the proximal femur (Figure 2A,C,D). The navigated pointer was then aimed in a craniodorsal and medial direction, to align the projection of the navigated pointer with the central long axis of the femoral neck, penetrating the acetabulum near the acetabular fossa (Video S1 and Figure 2A,C).

Once a satisfactory preliminary orientation and position of the projection were achieved, the surgeon stilled the images displayed on the monitor and put aside the navigated pointer. The stilled position of the tip of the navigated pointer was set as entry point and, after switching to "navigate projection," the tip of the projection was set as target. This resulted in a preliminary surgical plan for the drill corridor (Video S1 and Figure 2).

The preliminary plan was adjusted to ensure that the planned drill corridor did not engage the cortices of the femoral neck and exited the triangular shaped fovea capitis of the femur in a central position. In addition, the planned drill corridor had to cross the acetabular fossa dorsal and cranial to the base of the acetabular notch, thus penetrating a thick layer of bone yet avoiding the lunate surface of the acetabulum. To make these adjustments, the dorsal (annotated "axial" on the monitor of the navigation system) and transverse (annotated "coronal" on the monitor of the navigation system) reconstructions were selected and replaced trajectories 1 and 2. Moreover, the probe's eye view was selected and replaced the 3D reconstruction showing the medial aspect of the acetabulum (Figure 2). The probe's eye view presents a reconstructed plane that is perpendicular to the trajectory of the planned drill corridor. This perspective shows what the surgeon would see when looking along the shaft of an instrument that is perfectly aligned with the planned drill corridor. With the orientation provided by these views, the positions of the entry- and exit-points were repeatedly adjusted until the articular landmarks were achieved. A thorough final verification step of the planned drill corridor was performed in the probe's eye view to ensure that the planned drill corridor complied with all aforementioned criteria. This was rigorously performed in the cadaveric specimens included in the main study, after seemingly having neglected this verification step in the pilot trials. Finally, the plan of the drill corridor was shortened to set the entry point at the bone surface of the lateral femur and the surgical plan finalized, shown as a red line and a red dot in Figure 2 (Video S1).

2.4 | Navigated drilling and placing of the toggle construct

One surgeon experienced in CAS (CK) performed all navigated drilling procedures. A battery-powered surgical drill (Colibri II; DePuy Synthes, West Chester, Pennsylvania), mounted with a small instrument tracker (SureTrak II Universal Tracker, Large Passive Fighter, 961–581, Medtronic) and equipped with a 5.5 mm drill, was calibrated with the navigation system. The navigated pointer was used to determine the ideal position for the skin incision, by aligning its projection with the planned drill corridor. The tip of the navigated pointer was pressed into the skin to leave a temporary mark, then a 4 cm longitudinal skin incision was made, centered over the selected entry position, and extended through the superficial fascia, exposing the biceps femoris muscle. This was retracted caudally, exposing the proximal portion of the fascia of the vastus lateralis muscle, which was sharply incised longitudinally and the muscle fibers bluntly separated with Mayo scissors. Self-retaining Gelpi retractors were used to expose an approximately 1.5 cm^2 area of the lateral aspect of the femur. The navigated drill and sleeve were introduced until they contacted bone (Figure 3A).

With the orientation provided by the trajectory views 1 and 2, the operating surgeon positioned the tip of the drill on the planned entry point of the lateral femur. The "guidance view" was selected for display on the navigation monitor, replacing the remaining 3D volumetric reconstruction. The "guidance view" helped the surgeon with aligning the drill with the trajectory of the planned drill corridor and maintain this alignment during the navigated drilling procedure. The 5.5 mm bone canals were then drilled through the lateral cortex of the femur, femoral neck, femoral head and the acetabulum following the trajectory of the surgical plan displayed on the monitor of the navigation. During the drilling procedure, the navigation system provided the surgeon with real-time control over the orientation and penetration depth of the drill bit (Figure 3). In the experimental surgeries involving two whole cadavers of the pilot trials, particular care was taken when penetrating the medial cortex of the acetabulum, to avoid a forceful entry of the peritoneal cavity, thus preventing damage to abdominal viscera by the drill bit.

2.5 | Toggle construct placement

After penetrating the medial cortex of the acetabulum, the drill was withdrawn and replaced with a 14.5 cm long, 5.3 mm diameter sleeve (large transhumeral sleeve, AR-2845-2, Arthrex, Munich, Germany) and blunt-tipped 4.5 mm Steinmann pin as stylet. The sleeve stylet unit was used as a stabilizing element that traversed the coxofemoral joint, to ensure introduction of the toggle rod to an appropriate depth, preventing it from being inadvertently positioned in the coxofemoral joint space. The toggle construct was prepared by passing two strands of polyfilament suture material with an ultra-high molecular weight polyethylene core and a braided jacket of polyester (FiberTape 2 mm, 86 cm, Arthrex, Munich, Germany and TigerTape 2 mm, 76 cm, Arthrex), through

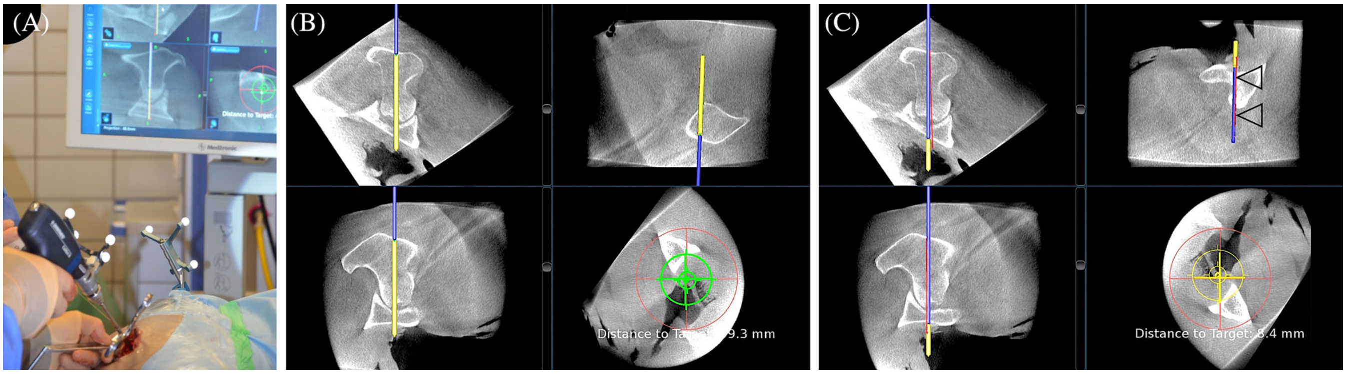

FIGURE 3 Illustration of the navigated drilling procedure. (A) Intraoperative photo showing a view of the StealthStation (Medtronic) navigation monitor presented to the surgeon, the navigated drill equipped with the instrument tracker, and the patient tracker fixed to the tuber coxae. Both trackers are facing the camera (not shown) of the optical tracking system, positioned cranially as shown in Figure 1. On the right, screenshots made at the beginning (B) and towards the end (C) of the drilling procedure are shown. The blue line represents the orientation and depth of the drill bit, as it follows the surgical plan (fine red line, highlighted by arrowheads in C). The yellow line is a projection of the drill. On the bottom right of each screen shot, the guidance view is shown, showing reconstructed images in a plane perpendicular to the drill bit. In addition, it displays the crosshairs of the guidance function to help the surgeon with aligning the drill with the trajectory of the planned drill corridor. Green crosshairs appear when correctly aimed at the surgical plan (A, B). Yellow crosshairs appear when aiming is suboptimal (C).

the cross-hole of an 18 mm long, 4 mm diameter stainless steel toggle rod (large toggle rod, 55040, IMEX Veterinary, Longview, Texas) (Figure 4). The FiberTape has a white and blue color, while TigerTape is colored white and gray, which permits each strand to be identified and the correct ends tied after the toggle has been positioned. After withdrawing the stylet from the sleeve, the toggle rod was passed through the sleeve, using a 3 mm blunt-tipped Steinmann pin as push rod, until the toggle rod exited the sleeve and bone canal, medial to the acetabulum. The Steinmann pin was then withdrawn and the toggle rod was securely locked transversely to the tip of the sleeve by gently pulling on the strands of the FiberTape until resistance was met. As the sleeve was withdrawn, light tension was applied to all suture strands until the toggle rod was seated against the medial surface of the acetabulum. The suture strands were then threaded through the four holes of an 8 by 12 mm stainless steel suture button (TightRope, VAR 8922, Arthrex) and the button advanced to the femur. Maximal tension (100 N) was applied to the pair of white and blue colored strands of the FiberTape using a tensioning device (suture tensioner with tensiometer, VAR-1529, Arthrex). The white and dark gray colored strands were then tied with a square knot over the suture button. The tensioning device was removed, the white and blue colored strands were tied with a square knot, and all suture ends were cut (Figure 4). Following placement of the toggle construct, the CBCT imaging unit was returned to its preoperative position and a postoperative scan acquired using the preoperative settings, to reproduce a field of view that corresponded to that of the preoperative scan. The cadaveric specimen was then turned and the same surgical procedure performed on the contralateral side.

2.6 | Dissection of cadaveric specimens to assess articular cartilage damage

Following completion of the bilateral experimental surgeries, each cadaveric specimen was dissected. In the two whole cadavers, the abdominal viscera were assessed for evidence of iatrogenic damage. This inspection included the serosal surfaces of the small and large intestines and the urinary bladder, with the possible outcome variables being “visible damage” versus “no lesion observed.” In each specimen, the positioning of the implants was assessed. The articular surfaces of the coxofemoral joints were examined grossly for evidence of iatrogenic articular cartilage damage at the entry and exit point of the bone canals. The results were categorized as “no cartilage damage,” “partial cartilage damage,” or “cartilage damage.” If the bone canals lay completely within the fovea capitis of the femur or the acetabular fossa, that is, without disturbance of the articular cartilage, it was defined as “no cartilage damage.” “Partial cartilage damage” was defined as a partial disruption of the marginal articular cartilage where the bone canals lay not entirely within the fovea capitis or the acetabular fossa. If the bone canals had not passed through either the fovea capitis or the acetabular fossa, the outcome variable was defined as “cartilage damage.” Toggle pinning was defined as “achieved,” if both

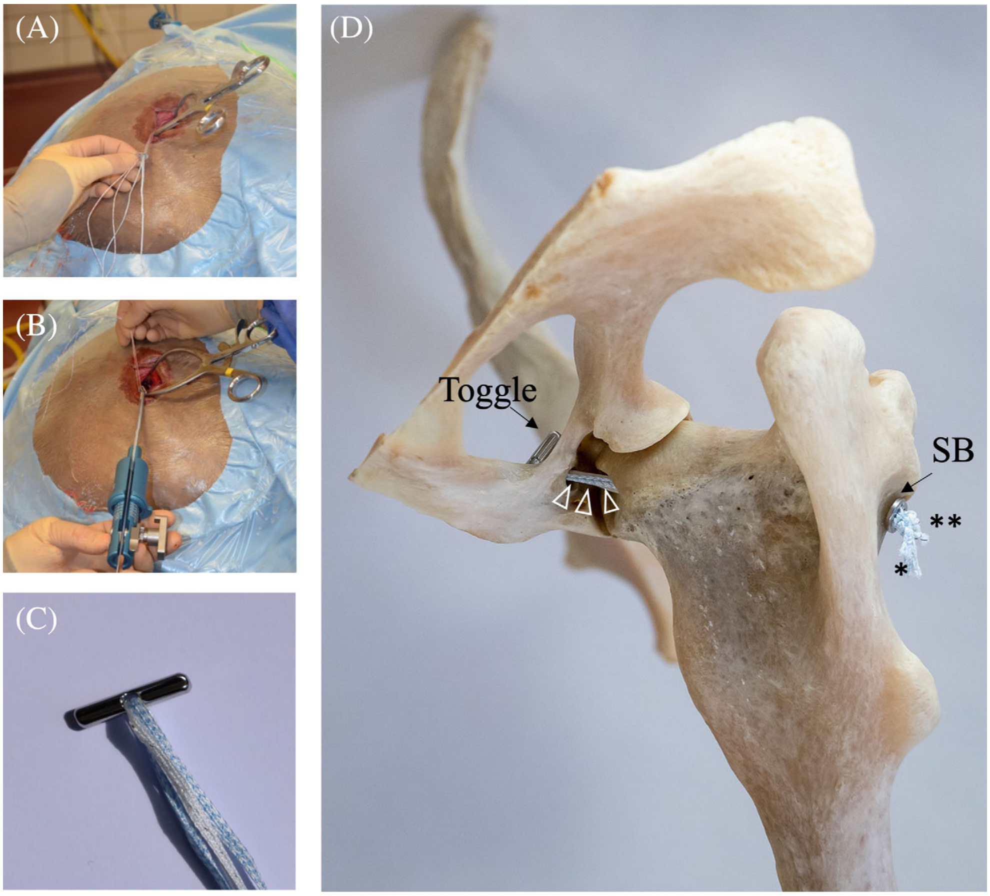

FIGURE 4 Illustrations depicting placement of the toggle pin. Intraoperative photos (A, B) showing the surgical approach to the right coxofemoral joint in a small equid. Illustrations of the implants (C, D). (A) The suture strands were threaded through the four holes of an 8 by 12 mm stainless steel suture button (TightRope, Arthrex) and the button is advanced to the femur. (B) Maximal tension (100 N) was applied to the strands of the FiberTape using a tensioning device (suture tensioner with tensiometer, AR-1529, Arthrex). (C) Toggle rod threaded with the FiberTape and TigerTape. (D) Caudoventral view of the fully assembled toggle pin construct in situ in a skeletal specimen of the right hemipelvis and femur. The toggle rod (Toggle) and metallic 4-hole suture button (SB), connected by a strand of FiberTape (*white and blue) and a strand of TigerTape (**white and dark gray).

metal implants were positioned in the desired anatomic locations and connected by the sutures, which traversed the coxofemoral joint. Specifically, the toggle rod had to be seated medially against the acetabulum and the suture button had to be seated against the lateral cortex of the femur.

2.7 | Surgical accuracy aberrations

The pre- and postoperative CBCT scans were merged using the StealthMerge function of the Cranial Software (Medtronic) (Figure 5A,B). Surgical accuracy aberrations (SAA) between the planned drill corridor and the created bone canal were determined as previously described.[23] The SAA is the distance (mm) measured between the center of the drilled bone canal and the center of the planned drill corridor as displayed in the probe's eye view. This ensured that the measurements were made in a plane perpendicular to the trajectory of the planned drill corridor, using the probe's eye planar reconstruction of the Cranial Software (Medtronic) (Figure 5C,D). For each experimental surgery, the SAA was measured at three sites: At the entry site into the lateral femur, at the exit site through the fovea capitis of the femur, and at the entry site into the acetabular fossa (illustrated with 3D rendered images in Figure 6). The following SAAs were calculated for each group separately (i.e., pilot trials and main study): A median SAA per drilling procedure for each cadaveric specimen, a median SAA per measurement site and for all cadaveric specimens, and an overall median SAA.

2.8 | Statistical analysis

The SAA measurements were analyzed using NCSS 12 statistical software (2018; NCSS, Kaysville, Utah).

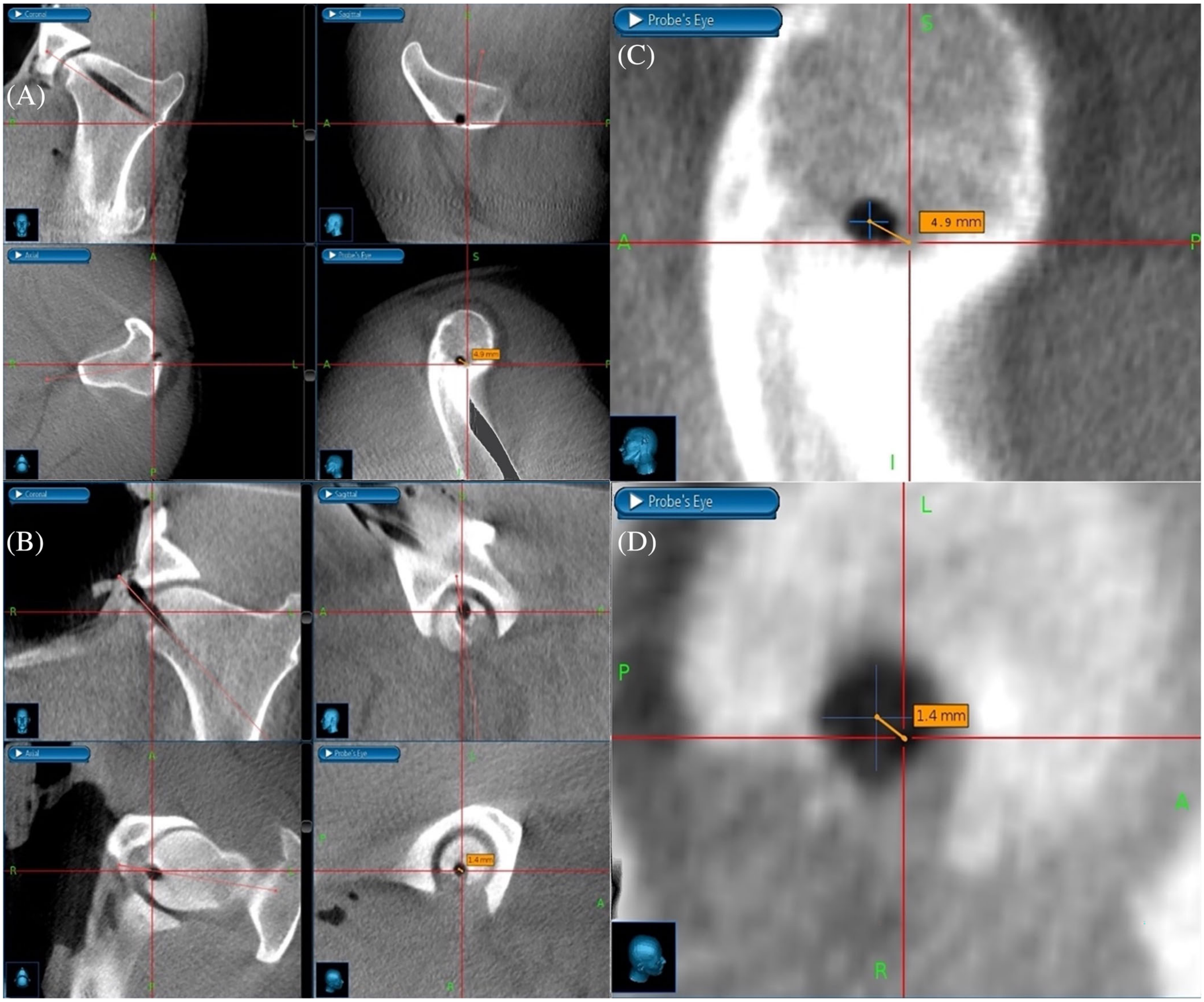

FIGURE 5 Screenshots of the multiplanar reconstructions of the merged pre- and postoperative cone beam computed tomographic scans used to measure the surgical accuracy aberrations (SAA) of pony 1. Images (C, D) are the magnified versions of the "probe's eye" images visible in the bottom right corner of (A, B), respectively. The center of the red crosshairs marks the axis of the surgical plan in each depicted plane. The SAA at the femoral entry site (A, C; 4.9 mm) and the exit site at the fovea capitis (B, D; 1.4 mm) are determined by measuring the distance between the center of the drilled bone canal and that of the planned drill corridor (center of the red crosshairs) in the "probe's eye" planar reconstruction of the Cranial Software (Medtronic). The "probe's eye" view shows a plane that is perpendicular to the trajectory of the planned drill corridor, in this study a slightly proximolateral-distomedial oblique sagittal plane of the femur.

Descriptive statistics were performed to assess the SAA of the drilling procedures at each of the three measurement sites, and separately for the specimens of the pilot trials and the main study. Furthermore, the overall median SAA was calculated for the navigated drilling procedures performed on the specimens included in the main study. Normality of the outcome variable distribution was assessed by visualization of frequency distribution and the Shapiro-Wilk test. The SAA between groups, that is, pilot trials and main study, were compared by using the Wilcoxon rank sum test. The significance level was set at $\alpha = 0.05$.

3 | RESULTS

The CBCT imaging unit consistently provided images of adequate quality to allow for surgical planning of the CAS procedure. Toggle constructs were successfully placed across all 18 coxofemoral joints of the nine

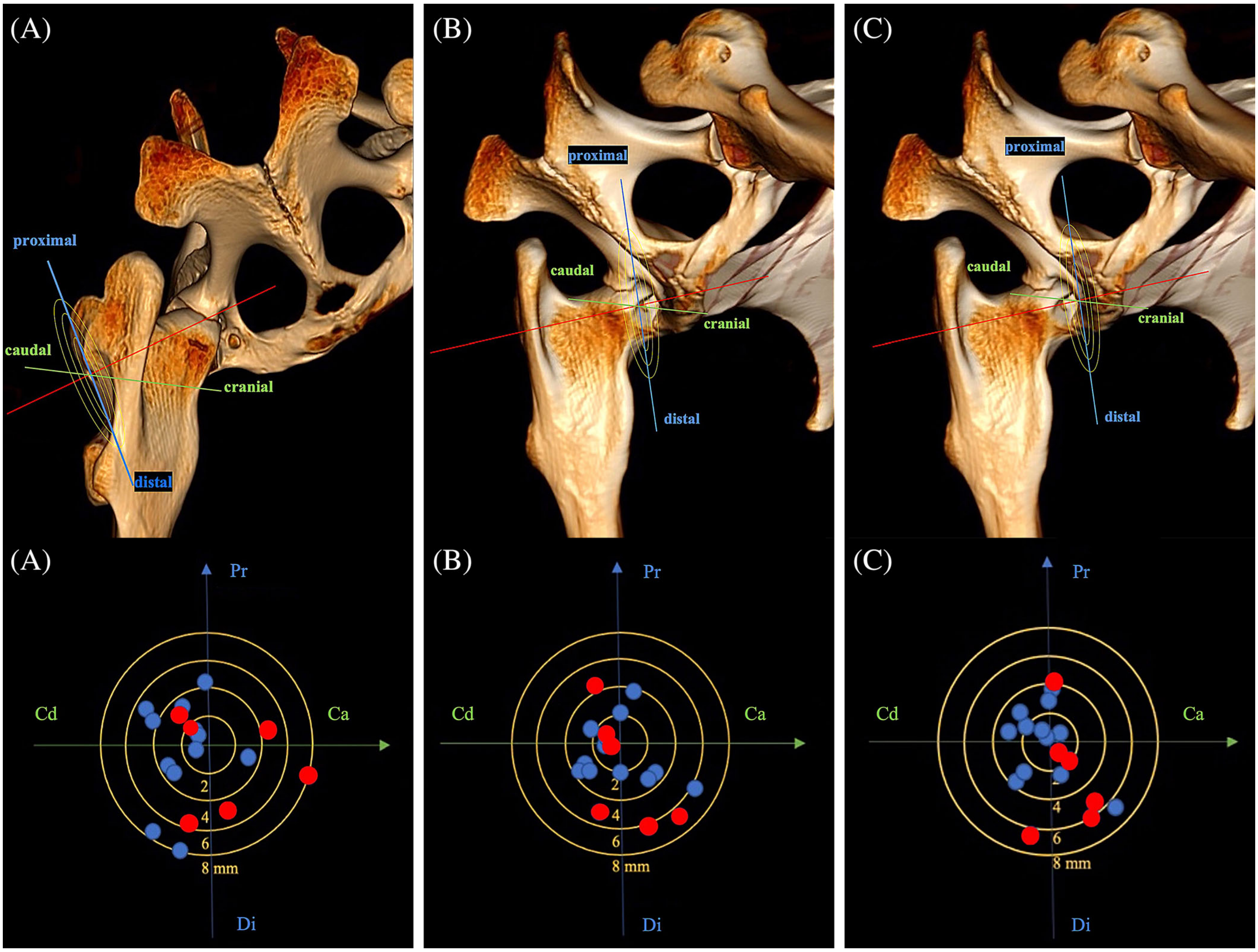

FIGURE 6 Illustration of the surgical accuracy aberration (SAA) measurements, using 3D volume rendered images of a helical computed tomography study of a skeletal specimen prepared from the pelvis of Pony 2. Caudoventral perspectives are provided. The perspective in (A), is more from caudal, than the more medial perspective in (B, C). SAA measurements were made at the entry site of the lateral femur (A), exit site from the femoral head at the level of the fovea capitis (B) and the entry site of the acetabulum (C). The red line represents the axis of the surgical plan. The green and blue lines represent the craniocaudal (or sagittal) and proximodistal (or long) axes, respectively, of the plane used for the SAA measurements, which is oriented perpendicular to the axis of the planned drill corridor. Bull's-eye targets are presented on the bottom half of each image, illustrating the direction (relative to the axis of the planned drill corridor) and magnitude of the measured SAAs of all experimental surgeries (blue dots) and of the pilot trials (red dots).

cadaveric specimens used in the pilot trials (3) and the main study (6).

3.1 | Gross dissection and assessment of iatrogenic articular cartilage damage

There was no evidence of iatrogenic damage to abdominal viscera in either of the two whole cadaveric specimens used in the pilot trials.

In the three cadaveric specimens used for the pilot trials, "partial cartilage damage" was detected in 2/6 and "cartilage damage" in 1/6 coxofemoral joints. Specifically, partial cartilage damage occurred in one joint of an adult Shetland pony and in another joint of one Warmblood foal, respectively. In these two joints, the bone canals partially exited at the border of the fovea capitis, causing damage to the marginal articular cartilage of the femoral head. In the joint of this Shetland pony, the drill tract also penetrated the border of the lunate surface of the acetabulum. "Cartilage damage" was noted in the other coxofemoral joint of the pilot foal specimen, in which the drill fully penetrated the femoral head adjacent to the fovea capitis causing a focal, full-thickness lesion of the articular cartilage of the femoral head and at the border of the lunate surface of the acetabulum (Figure 7).

In all 12 coxofemoral joints of the main study, the bone canal exited the femur in the fovea capitis and

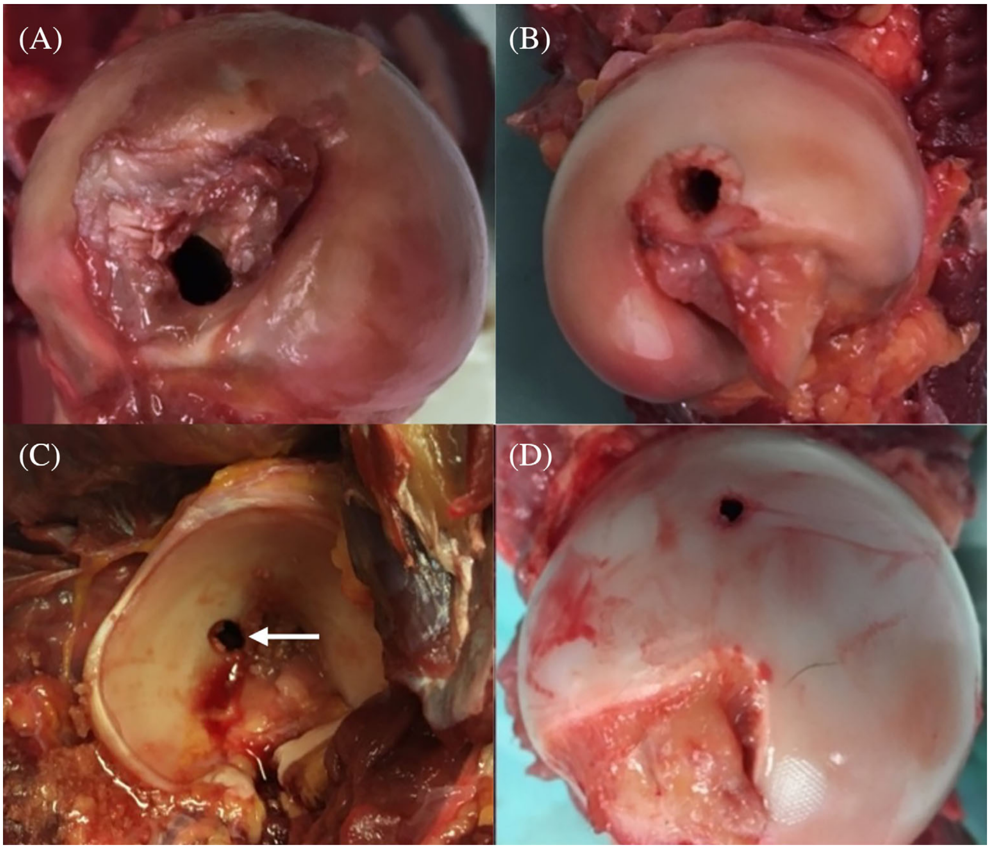

FIGURE 7 Cadaver dissections demonstrating “no cartilage damage” (A; study specimen Donkey 2), that is, the drill has penetrated the femoral fovea capitis and not engaged any articular cartilage. “Partial cartilage damage” (B, C; both in the right coxofemoral joint of pilot specimen Pony 1), the drill partially disrupted articular cartilage at the margin of the fovea capitis (B) and the lunate surface of the acetabulum (C; white arrow), respectively. “Cartilage damage” (D; right coxofemoral joint of pilot specimen Foal 1), the drill has penetrated the articular cartilage of the femoral head and not the femoral fovea capitis.

acetabular fossa, causing no damage to the articular cartilage of the femoral head and the lunate surface of the acetabulum.

3.2 | Surgical accuracy aberrations

The measured SAAs (mm) per drilling procedure at each of the three measurement sites, and the calculated median SAA per drilling procedure, that is, per specimen, and separated by group (i.e., pilot trials and main study), are shown in Table 2. Direction and magnitude of all measured SAAs are graphically illustrated for each of the three measurement sites in bull's-eye targets in Figure 6. The overall median SAA for the specimens of the main study was 2.8 mm (range: 0.4–8.0 mm). No statistically significant differences were found when comparing the SAAs measured in each group, that is, pilot trials versus main study ($p = 0.2$ at each measurement site).

4 | DISCUSSION

Based on the results of this experimental cadaveric study, a toggle construct can be placed in a minimally invasive manner using CAS guidance across the coxofemoral joints of small equids without prior luxation. However, particularly the surgical planning of the CAS procedure has a steep learning curve, leaving little room for error. This is reflected in the high incidence of iatrogenic articular cartilage damage found in the pilot specimens. In clinical cases, the technical setup described here may be associated with a considerable risk of iatrogenic damage to the articular cartilage, because the coxofemoral joints of equids affected by coxofemoral luxation, even following closed reduction, are arguably less stable than the joints used in this study. Nonetheless, when performed by a surgical team experienced in CAS and proficient in the complex surgical planning of this procedure, this technique may serve as a minimally invasive surgical option to provide surgical stabilization of luxated coxofemoral joints following successful closed reduction.

4.1 | Iatrogenic cartilage damage

The postoperative gross dissection and inspection of the cartilage surfaces of the coxofemoral joint revealed partial articular cartilage damage in two out of three pilot specimens: one pony and one foal specimen. The focal full-

TABLE 2 Surgical accuracy aberration (SAA) measurements at each of the three measurement sites in all coxofemoral joints, listed in chronological order in which the experimental surgeries were performed.

Cadaveric specimen	SAA at the entry into the femur (mm)	SAA at the exit of the femur (mm)	SAA at the entry into the acetabulum (mm)	Median SAA per drilling procedure (mm)
Donkey 1 L	4.9	6.7	6.2	6.2
Donkey 1 R	1.9	0.5	1.3	1.3
Pony 1 L*	3.5	1.4	2.1	2.1
Pony 1 R* ←	4.9	1.4	4.3	4.4
Foal 1 L* ←	8.0	6.4	5.5	6.4
Foal 1 R* ←	5.9	5.1	6.5	5.9
Median per measurement site (pilots only)	4.9	4.8	4.9	/
Range (pilots)	1.9–8.0	0.5–6.7	1.3–6.5	/
Donkey 2 L	2.0	1.1	1.2	1.2
Donkey 2 R	8.0	6.4	6.5	6.5
Pony 2 L	4.4	3.0	1.2	3.0
Pony 2 R	3.3	0.4	2.8	2.8
Pony 3 L	2.5	2.4	2.8	2.5
Pony 3 R	2.8	1.3	0.7	1.3
Pony 4 L	0.8	2.0	2.4	2.0
Pony 4 R	7.2	3.7	3.9	3.9
Pony 5 L	4.4	2.8	2.2	2.8
Pony 5 R	3.7	2.9	2.7	2.9
Foal 2 L	2.9	3.9	3.8	3.8
Foal 2 R	1.5	2.2	2.8	2.2
Median per measurement site (main study only)	3.1	2.6	2.8	/
Range (main study)	0.8–8.0	0.4–6.4	0.7–6.5	/

Note: L, left coxofemoral joint; R, right coxofemoral joint. The first three cadaver specimens were used for pilot trials (gray font). The arrow (←) indicates specimens in which cartilage damage occurred.

*The whole cadaver was frozen and used for the experiment.

thickness cartilage lesion in the pilot foal specimen was most likely due to erroneous surgical planning. In this pilot procedure, the drill corridor was erroneously planned too close to the proximal tip of the femoral fovea capitis instead of being centered in the triangular area. This was missed because the surgical planning of the pilot trials lacked a final control step, emphasizing the need for a thorough final verification of the planned drill corridor in the probe's eye view to ensure that the planned drill corridor is centered in the fovea capitis. In the specimens enrolled in the main study, cartilage damage to the femoral fovea capitis did not occur in any of the experimental surgeries, even in specimens for which the SAA measurements at the exit point of the femur were higher compared to those measured in some of the pilot trials.

4.2 | Surgical accuracy aberrations

To our knowledge, this is the first description of a minimally invasive CAS toggle pinning technique performed on the coxofemoral joint of small equid cadaveric specimens. Hence, meaningful comparisons can only be made with similar techniques described for other species. In dogs, the cartilage damage resulting from minimally invasive toggle pinning of the coxofemoral joint has been assessed in three cadaveric studies.[18–20] The incidence of iatrogenic cartilage damage created during the CAS toggle pinning described here is lower compared to those reported in the experimental studies in dogs. In the most recent study, using 3D-printed drill-guides, 15% of the drill corridors were “inside” the femoral fovea capitis.[18] In the other two experimental studies in dogs, and using fluoroscopic guidance, 25% and 64% of the toggle pin constructs were placed without cartilage damage, respectively.[19,20] This is in contrast to the present study, where no cartilage damage occurred in any of the specimens enrolled in the experiments of the main study. These surgeries, however, were performed after the surgical team had gained proficiency in the CAS procedure by conducting a series of pilot trials. The pilot trials allowed to optimize the surgical planning and standardize this crucial part of the CAS procedure. Importantly, the standardized protocol for surgical planning included a final control step to ensure a safe distance between the planned drill corridor and the articular surfaces of the femoral head. When including the specimens used for the pilot trials, cartilage damage occurred in 3/18 (17%) of the operated joints. This is similar to what is reported in the study using 3D-printed drill-guides.[18]

The comparison of the SAA measured in the pilot trials versus the SAA measured in the main study, revealed no statistically significant difference in surgical accuracy between these two groups. This indicates the lack of a learning effect in navigated drilling for this procedure, possibly explained because it was performed by a surgeon already experienced in navigated drilling. However, combined with the finding that articular cartilage damage only occurred in pilot specimens, this supports the authors' impression that they experienced a steep learning curve for the challenging surgical planning of the procedure.

Compared to CAS-guided drilling of the proximal phalanx of horses using the same equipment for imaging and navigated drilling, the overall median SAA was considerably higher in the present study (2.8 vs. 0.7 mm).[23] We suggest that the greater instability of the experimental CAS setup described here, is the most important factor contributing to this increase. In the CAS setup of the present study, the calf jack serves as a stabilizing element to maintain the femur and pelvis in an angle-stable and fixed position. This is of critical importance in CAS and optical tracking when targeting two separate but articulating bones. The femur is the primarily targeted bone, but the patient tracker is fixed to the pelvis. Therefore, it is of critical importance that both femur and pelvis remain in an unchanged spatial arrangement, during both image acquisition and the navigated surgical procedure. Any disturbance of this spatial arrangement will lead to an increase in SAA. Compared to the stabilization achieved with the combination of calf jack and tripod, the purpose-built frame used for CAS of the equine distal extremity is a more compact and stable construct. It is tightly connected to the hoof and cannon bone,[23] which are linked by hinge joints. The coxofemoral joint, on the other hand, is a ball-and-socket joint deeply imbedded in the soft tissues, allowing for motion in several planes. Therefore, it is more difficult to provide an angle-stable fixation of this anatomical region. Further clinical research is needed to assess if this may limit the use of this technique.

4.3 | Strategic positioning of the patient tracker

In computer-assisted orthopedic surgeries with optical tracking, the patient tracker is normally placed directly on the targeted bone.[26,27] As mentioned above, in the setup of this investigation, this would be the femur, as the first bone canal of the navigated drilling procedure is through the femoral neck and head. However, in anticipation of applying this technique in clinical cases, we elected to place the patient tracker remotely on the tuber coxae. This prevents interference with the patient tracker while manipulating the lateral aspect of the hip when performing a closed reduction of the coxofemoral joint. The remote positioning avoids possible superimposition of patient- and instrument-tracker during the surgical procedure, which would prevent the navigation, as both trackers need to be identified separately by the infrared camera to allow accurate 3D orientation of the surgical instrument. In smaller subjects, such as small breed dogs, with a smaller femoral neck and head, improved surgical accuracy could be achieved if the patient tracker is placed directly on the femoral shaft. Alternatively, or in addition, a spherical head screw may be placed on the femur as a fiducial marker prior to acquiring the preoperative scan. This would allow for repeated intraoperative accuracy checks, as it has been described for navigated drilling procedures on equine distal extremities in an experimental setting.[23] Another possibility is the use of two separate patient trackers, that is, one on the pelvis and the other on the femur, similar to what is described for total knee arthroplasty computer navigation in humans.[27]

4.4 | Limitations

A major limitation of this study is the use of cadaveric specimens without prior coxofemoral joint luxation and associated instability due to tearing of soft tissue support structures. Therefore, a loss in surgical accuracy with an increased risk of iatrogenic damage should be considered, when transferring this technique into clinical trials. Although all cadavers were operated using the same surgical protocol, the learning curve associated with the complex surgical planning of the procedure meant that the pilot cadaveric specimens were at a higher risk for errors in surgical planning. This is reflected by the fact that articular cartilage damage only occurred in cadaveric specimens used for the pilot trials. Furthermore, the study has a low number of whole cadavers used for the assessment of the potential risk of damage to abdominal viscera or to neurovascular structures that run in the obturator sulcus deep to the acetabulum. A more homogeneous study population consisting of whole cadavers of skeletally mature small equids would have improved the study.

Further experimental investigations and clinical experiences are required to determine the ideal position of the toggle construct to achieve the most functional results in terms of biomechanical stability. The strength, stability and required tension of the toggle construct are unknown. Braided ultrahigh-molecular-weight polyethylene suture materials have been used for coxofemoral luxation repair in small animal surgery with favorable success rates,[16] and in a single pony treated with a combination of a modified toggle pin technique and prosthetic capsular reconstruction.[11] However, the present study does not provide data that would indicate that the type of prosthesis used is adequate for clinical use. Hence, further research is needed to assess the biomechanical suitability and the required tension of such toggle constructs for the use in small equids.

We conclude that in small equid cadaveric specimens without prior luxation of the coxofemoral joint, the CAS technique described here allows placement of a toggle construct across the coxofemoral joint using a minimally invasive approach. However, the technique relies on a calf jack to maintain stability between the femur and pelvis, with the patient tracker being attached to the tuber coxae and not directly to the primarily targeted femur. Hence, the setup may be less stable and prone to greater SAAs compared to setups that involve a patient tracker arrangement directly on the femur. The accuracy of the navigated drilling procedure may be lower in previously luxated and then reduced coxofemoral joints, and additional clinical research is needed to determine the consequences of this limitation. Furthermore, experimental biomechanical investigations are required to optimize implant positioning and the suitability of toggle constructs for the purpose of stabilizing the coxofemoral joint in small equids.

AUTHOR CONTRIBUTIONS

Claeys I, DVM: Contributed to all parts of the project and prepared a first draft of the manuscript. van der Vekens E, DVM, PhD, DECVDI: Involved in study design, imaging, and operative planning, and critically revised the manuscript for important intellectual content. Kümmerle J, PhD, DECVS: Involved in study design, development of the surgical technique, and critically revised the manuscript for important intellectual content. de Preux M, DECVS: Involved in imaging and operative planning, and critically revised the manuscript for important intellectual content. Koch C, DACVS, DECVS: Initiated the project and contributed to all aspects of the experimental study and manuscript preparation. All authors contributed substantially to this project and the resulting publication.

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CONFLICT OF INTEREST STATEMENT

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

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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