Received: 24 February 2020 | Revised: 30 April 2020 | Accepted: 6 June 2020

DOI: 10.1111/vsu.13484

ORIGINAL ARTICLE - RESEARCH

WILEY

Influence of a purpose-built frame on the accuracy of computer-assisted orthopedic surgery of equine extremities

Mathieu de Preux Med Vet[1,2] | Beatriz Vidondo MScBiol, MSc, IT, PhD[3] | Christoph Koch Dr Med Vet, DACVS, DECVS[1,2]

[1]Swiss Institute of Equine Medicine, Vetsuisse-Faculty, University of Bern, Bern, Switzerland

[2]Agroscope, Avenches, Switzerland

[3]Swiss Institute for Veterinary Public Health, Vetsuisse-Faculty, University of Bern, Bern, Switzerland

Correspondence
Christoph Koch, Swiss Institute for Equine Medicine, Vetsuisse-Faculty, University of Bern, Länggassstrasse 124, Postfach 8466, 3001 Bern, Switzerland.
Email: christoph.koch@vetsuisse.unibe.ch

Abstract

Objective: To determine the influence of a purpose-built frame on the accuracy of screw placement during computer-assisted orthopedic surgery (CAOS) of the equine extremity.

Study design: Experimental cadaveric study.

Sample population: Twenty-four paired equine cadaveric limbs obtained from seven horses.

Methods: Three 4.5-mm cortex screws were inserted in lag technique in three different planes of orientation in the proximal phalanx (P1) by means of CAOS. In the study group (n = 12 limbs), the tracker was anchored on a purpose-built frame designed to stabilize the extremity. In the control group (n = 12 limbs), a conventional tracker array was used that was anchored directly on P1. The stability of both tracker arrays was assessed during the procedure by using fiducial markers. After screw placement, preoperative and postoperative computed tomographic images were assessed to measure surgical accuracy aberrations (SAA) between the planned and achieved screw position. Descriptive statistics and repeated-measures analysis of variance were performed to compare SAA measurements between the study and control group.

Results: Both tracker arrays remained consistently stable in all specimens. Mean overall SAA of screw insertion were lower in the study group (0.7 mm; median, 0.5; range 0-3.4) than in the control group (1.2 mm; median, 0.9; range, 0-4.2 mm).

Conclusion: The mean SAA achieved in cortex screw placement using CAOS lies within the range of approximately 1 mm. The use of a purpose-built frame avoided additional drilling of the target bone and improved surgical accuracy compared with the conventional tracker array.

Clinical significance: The purpose-built frame described in this report can be used to facilitate CAOS in equine orthopedics without compromising surgical accuracy.

1 | INTRODUCTION

Numerous indications in equine orthopedic surgery demand the highest possible precision in cortex screw placement, leaving little room for error. Preoperative and intraoperative three-dimensional (3D) image guidance help increase the accuracy of cortex screw placement and set new standards in precision.[1-6] In addition, aiming devices[5,7] are used to increase accuracy of drilling procedures. Moreover, purpose-built constructs have been introduced to maintain the leg in a forcefully extended position to stabilize the target bone[5,6,8] and to avoid loss of landmarks[9] during imaging-assisted surgery. Ultimately, these devices and constructs optimize surgical accuracy and increase control over the drilling procedure. However, the authors of several reports have emphasized the importance of refinement of equipment and technique to improve efficiency and shorten surgery times.[6,9]

Computer-assisted orthopedic surgery (CAOS) considerably enhances the precision of screw insertion compared with conventional intraoperative 2D and 3D image-guided techniques with or without the additional help of aiming devices.[1-3,10,11] The required equipment for CAOS is becoming increasingly available in veterinary referral centers and is used for surgical interventions that demand extreme precision such as total knee replacements[12] in dogs and cortex screw placement for the repair of distal phalangeal[1,3,13,14] and sesamoid bone[2,15] fractures in horses.

In the early 2000s, mobile computed tomography (CT) units coupled with user-friendly computer-assisted surgical navigation systems were introduced to the market. One such device (StealthStation; Medtronic Navigation, Louisville, Colorado) combines a navigation system with a mobile cone beam computed tomography (CBCT) unit that readily accommodates all areas of the equine extremity including the elbow and the stifle. These features make it an ideal tool for CAOS applications in horses. The authors have gained considerable first hand expertise with this technology at their veterinary teaching hospital.[16] The manufacturer of the surgical navigation system used in the present study demonstrated a positional accuracy with a mean error ≤ 2 mm.[17] This would represent an adequate benchmark for the majority of lag-screw repairs in equine orthopedic surgery.

One distinct disadvantage inherent to this and other surgical navigation systems is the requirement to securely anchor a tracker equipped with infrared reflective marker spheres to the target bone.[18] For this purpose, pins or screws are drilled into the target bone to create a rigid and angle-stable fixation. Depending on the integrity, size, and location of the target bone, this may lead to significant morbidity of the bone or adjacent soft tissue structures.[18] To overcome the disadvantages associated with anchoring the tracker directly on the target bone while still providing the required stability for accurate navigation, a versatile frame to facilitate CAOS applications involving the equine distal extremity was developed at the authors' institution.

The objective of this study was to assess the function and accuracy of this purpose-built frame for predefined navigated drilling procedures of the proximal phalanx and to identify potential sources of imprecision. On the basis of preliminary experiments and the our clinical experience, we hypothesized that

1 The use of a purpose-built frame, with the tracker anchored on the frame and not on the target bone, would result in accurately positioned drill tracts. Specifically, it was predicted that the mean discrepancies between planned and executed drill tracts, hereafter referred to as *surgical accuracy aberrations* (SAA), would be less than 2 mm.
2 The use of a purpose-built frame would not result in any significant loss of surgical accuracy compared with the conventional setup in which the tracker is connected directly to the target bone.

2 | MATERIALS AND METHODS

2.1 | Purpose-built frame

A frame was designed that would be able to maintain either a thoracic or pelvic equine limb in an extended, near–weight bearing position during a surgical intervention in either right or left lateral recumbency (Figure 1). This purpose-built frame was manufactured from a hard plastic polymer (polyoxymethylene) to avoid interference from electromagnetic radiation and to allow for formaldehyde gas sterilization. A modified hoof shoe (Ultimate; NANRIC, Lawrenceburg, Kentucky) and two proximal-to-distal adjustable y-shaped plastic pillars were added to tightly secure hoof and third metacarpal/metatarsal bone (MCIII/MTIII) to the frame. The modifications were made to four different hoof shoe sizes (6-9), which can be interchanged so that the construct can accommodate different hoof sizes and conformations. Furthermore, slots were preplaced in strategic locations (Figure 1) to firmly attach the tracker to the frame with commercially available spinous process clamps (open spine clamp; Medtronic; Figure 2).

A series of preliminary experiments were conducted to test prototypes of this frame and to develop the protocol for the experimental study.

2.2 | Study design

Paired thoracic and pelvic cadaveric limbs from client-owned horses that had been euthanized for reasons unrelated to orthopedic disease were collected. All owners signed an informed consent form, permitting the use of tissues and images for teaching and research

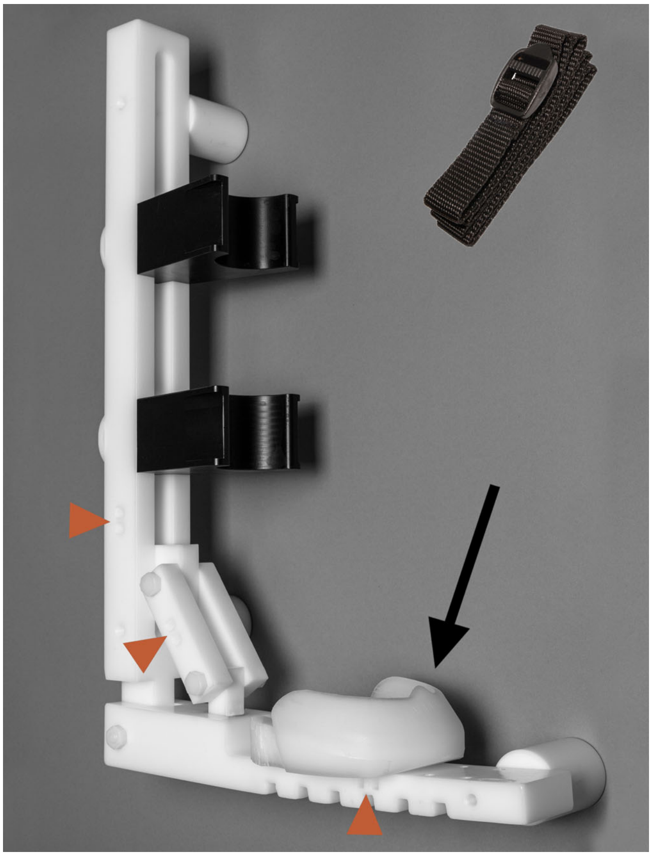

FIGURE 1 The purpose-built frame with a modified NANRIC Ultimate hoof shoe (arrow) and two (black) y-shaped pillars. Tie down straps (2 cm wide) with plastic ladderlock buckles (at top right) are used to fasten the hoof and third metacarpal/metatarsal bone to the hoof shoe and pillars, respectively. Four plastic screws fix the hoof shoe to the horizontal arm of the frame in which screw holes have been predrilled at equal distances. Thus, hoof shoes of different sizes are readily exchanged, and their position can be adjusted in the dorsal-to-palmar/plantar direction. The position of the y-shaped pillars is adjustable in the proximal-to-distal direction so that the construct can accommodate different hoof sizes and pastern conformations. The strategically preplaced slots (arrowheads) anchor the spinous process clamp that holds the patient tracker

purposes. After disarticulation of the limbs at the level of the carpometacarpal or tarsometatarsal joint, the limbs were stored at −20°C and thawed at room temperature for 36 to 48 hours prior to conducting the experiments.

2.3 | Preparation of cadaveric specimens

Shoes were removed when they were present, and the hooves were cleaned and trimmed. The appropriate size shoe was selected for each hoof. The distal extremity was clipped from the coronary band up to 10 cm proximal to the metacarpophalangeal metatarsophalangeal joint. The limb was then tightly secured in the purpose-built frame (Figures 1 and 2). A vertical stab incision was made over the palpable eminence for the attachment of the lateral collateral ligament on the distal proximal phalanx (P1) lateral to the common/long digital extensor tendon. After predrilling through the cortical bone with a 1.5-mm drill bit, a 10-mm radiopaque spherical head screw (SHS; Unibody Bone Fiducial; Medtronic) was placed on each specimen. The SHS, positioned in the distal lateral aspect of P1, served to detect any deviation of the target bone in relation to the tracker array. At this time, one of the paired limbs was assigned to either the study group or the control group by the toss of a coin, and the contralateral limb was automatically allocated to the other group.

In all limbs assigned to the control group, the tracker was anchored as distal as possible on two 3.2-mm pins placed into the dorsal aspect of P1. Two vertical stab incisions through the skin and the underlying common/long digital extensor tendon (Figure 2A) were made to visualize pin placement. In contrast, the tracker was anchored on the frame to all limbs assigned to the study group (Figure 2B).

2.4 | Computed tomography and preoperative planning

Preoperative and postoperative CT images of each cadaveric specimen were acquired with a CBCT-based navigation system (O-arm and StealthStation; Medtronic). The limb and frame were placed on a carbon table (General Medical Merate SPA, Bergamo, Italy) routinely used for CBCT imaging at the authors' veterinary teaching hospital. This setup corresponded to that of a routine CAOS procedure in a horse surgically treated in lateral recumbency. For each scan, it was ensured that the localizer camera simultaneously detected the reflecting spheres of the patient tracker and the infrared light-emitting tracker of the O-arm gantry and that the entire region of interest was part of the image volume. The resulting 3D images were automatically exported from the O-arm to the StealthStation.

Preoperatively planning of screw positions was performed in Cranial Software (Medtronic). For screw 1, a 4.5-mm cortex screw was placed in lag fashion, mimicking the repair of an imaginary proximal midsagittal P1 fracture (Figure 3, blue line). The line representing the center of the core axis of the screw (Figure 3, red line) was placed 5 mm from the most distal point of the sagittal groove, perpendicular to the sagittal plane, midway between the dorsal and palmar/plantar limits of the bone, and parallel to the articular surface of the metacarpophalangeal metatarsophalangeal joint. For screw 2, a second 4.5-mm cortex screw was inserted in

FIGURE 2 The computed tomography-based surgical navigation system immediately after image acquisition. The cadaveric limb is secured in the purpose-built frame and placed on a carbon table. A, The tracker is anchored to the dorsal aspect of the proximal phalanx using two 3.2-mm pins as distal as possible (control group). B, The tracker is anchored directly to the frame (study group)

lag fashion in a dorsolateral-palmaro/plantaromedial oblique direction (Figure 3, purple line), angled 45° from the first screw in a transverse plane 10 to 15 mm distal to the plane of insertion of screw 1. For screw 3, a 4.5-mm cortex screw was inserted in lag fashion in the midsagittal plane of the extremity to mimic the repair of an imaginary frontal plane P1 fracture (Figure 3, green line). The entry of the screw was 10 to 15 mm distal to screw 2 and was directed from dorsal to palmar/plantar in the sagittal plane, midway between the lateral and medial border of P1 (Figure 3, orange line).

For all three screws, an imaginary fracture plane was assumed and drawn on the operative plan. Thus, the penetration depth of the drill bit was closely monitored during all drilling procedures as it would be in a clinical case when one is operating on a nondisplaced or anatomically reduced fracture.

2.5 | Computer-assisted surgical procedure

After preoperative planing had been completed, the "navigation" mode was selected, and trajectories 1 and 2 as well as the guidance function were displayed on the screen for orientation (Figure 3). All drilling procedures were performed by the same surgeon (C.K.). After identification of the planned screw entry site by using the

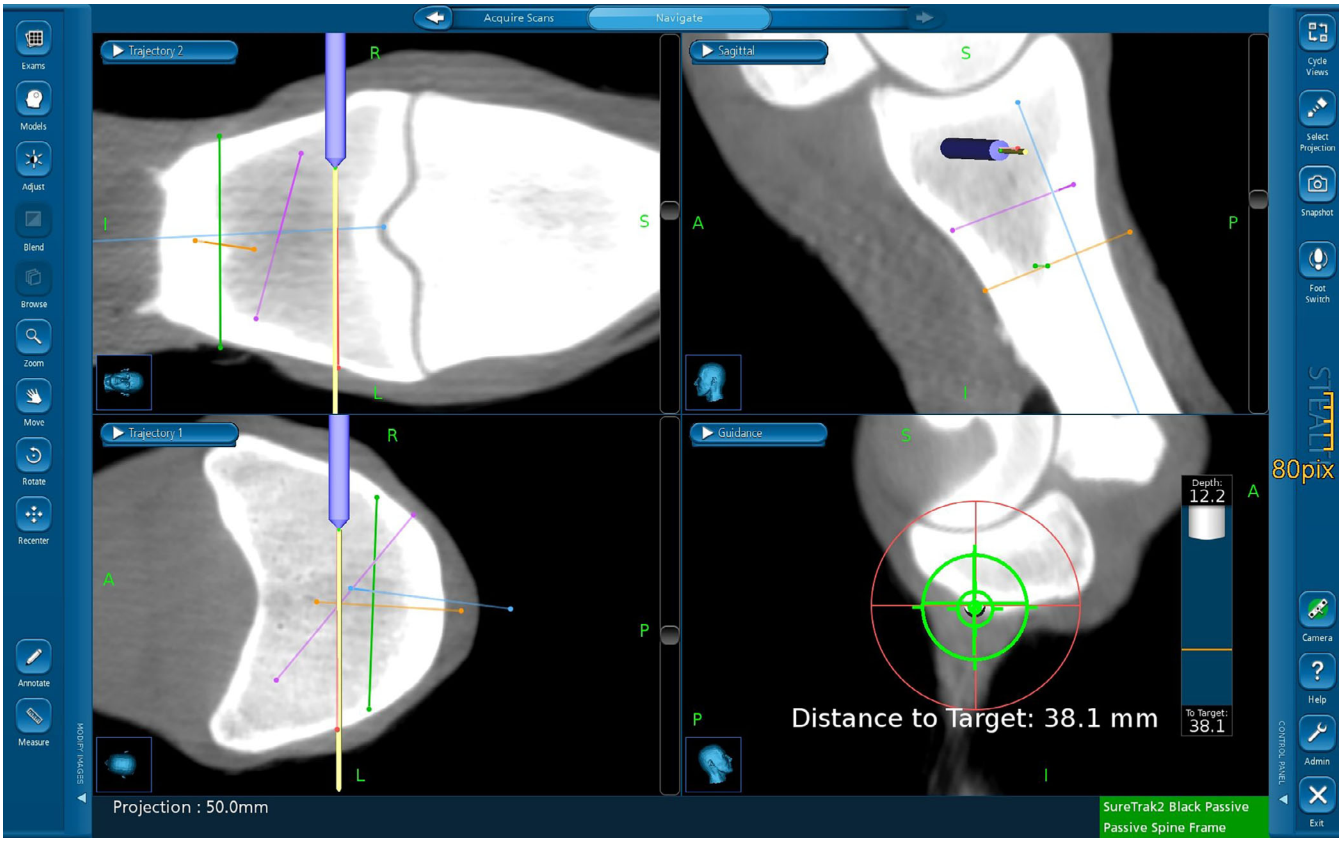

FIGURE 3 Intraoperative screenshot. The proximal aspect of the proximal phalanx is projected in three different planes (top left, dorsal; bottom left, transverse; top right, sagittal). The planned screw positions are illustrated by red, purple, and orange lines. The drill bit (4.5-mm-wide blue cylinder) has penetrated the near cortex. The projection of the drill bit (narrow yellow cylinder) and a target-grid (bottom right) were used for navigation

FIGURE 4 Spatial interference during a drilling procedure. The patient tracker (anchored to the proximal phalanx, control group) and the instrument tracker mounted on the drill are superimposed, impeding proper detection of the trackers by the localizer camera

navigated pointer (sharp pointer; Medtronic), the free-hand navigated drilling procedure was started. A stab incision with a No. 11 scalpel blade was made to access the near cortex of the target bone. A short (147 mm) 4.5-mm drill bit attached to a battery-powered surgical drill (Colibri II; DePuy Synthes, West Chester, Pennsylvania) mounted with reflecting spheres (SureTrak II clamps and tracker; Medtronic) was registered and calibrated. There was no requirement to seperately calibrate the 3.2-mm drill bit because as its length is identical to that of the short 4.5 mm drill bit.

When there was interference between the drill and tracker (Figure 4), a longer (197 mm) drill bit was used, requiring recalibration of the drill. When interference could not be resolved by switching to a longer drill bit, the tracker was reoriented on the preplaced pins, and the preoperative scan was repeated. Every interference was recorded.

For each screw, drilling of the 4.5-mm glide hole and 3.2-mm thread hole was performed while orientation and drill bit penetration depth were controlled with the StealthStation surgical navigation. However, the navigation system was not used for screw head countersinking, depth measurement (both manual depth-gauge and CBCT-measurements were documented), or thread cutting. Finally, a cortical screw of the appropriate length (based on the manual length measurement) was inserted and tightened to approximatly 4 N-m of torque. Skin incisions were not closed. Immediately after insertion of screw 3, a first postoperative CBCT scan was performed. All screws were subsequently removed, and a second postoperative scan was performed to allow for artifact-free assessment of the drill tracts.

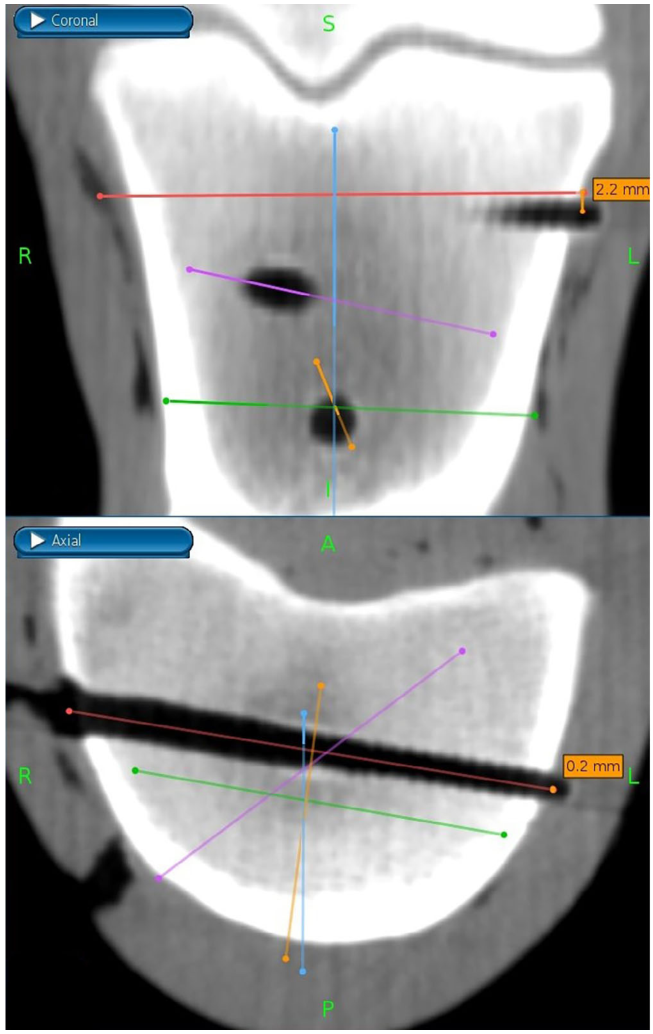

FIGURE 5 Merged preoperative and postoperative cone beam computed tomography images, dorsal (= coronal) and transverse (= axial) planes. The surgical accuracy aberration (in millimeters) was assessed by using the StealthStation measuring function at the exit point of the drilled tract, in the dorsal (dorsal exit imprecision = 2.2 mm) as well as the transverse (transverse exit imprecision = 0.2 mm) plane of the proximal phalanx. Blue line, imaginary proximal midsagittal proximal phalanx fracture. Red line, planned core axis of the drill hole for the first 4.5-mm cortex screw. Purple line, planned core axis of the drill hole for the second 4.5-mm cortex screw. Green line, imaginary frontal plane proximal phalanx fracture. Orange line, planned core axis of the drill hole for the third 4.5-mm cortex screw

2.6 | Assessment of tracker array stability

The accuracy of the navigation system and the stability of the tracker array were repeatedly controlled by positioning the tip of the navigated pointer in the central pit of the head of the SHS between every procedural step in both groups. According to the definition determined prior to study execution, significant loss of tracker array stability, also termed *fiducial localization error*,[19] was documented only when the pointer tip no longer displayed contact with the virtual image of the screw head when placed in the core of the SHS. The diameter of the SHS screw head measured 5 mm, meaning that, in case of appropriate registration, only a loss in accuracy exceeding 2.5 mm in any dimension away from the central pit of the screw head would have been detected by regularly checking the SHS position. Each procedure was performed with a checklist to assure that all steps and measurements were consistently performed between procedures.

2.7 | Assessment of surgical accuracy

For each cadaveric limb, the preoperative CBCT scan, including the operative plan, was merged with the postoperative CBCT scan in the StealthMerge function of the Cranial Software. The deviation (in millimeters) of the center of the actual drill track from the line representing the axis of the planned drill track was measured in four predefined locations and planes. Briefly, for each screw, the SAA were measured at the entry and exit point in the long axis of P1, referred to as *DENI* (entry imprecision in the dorsal plane) and *DEXI* (exit imprecision in the dorsal plane), as well as the short axis of P1, referred to as *TENI* (entry imprecision in the transverse plane) and *TEXI* (exit imprecision in the transverse plane; Figure 5).

Even though the study and control groups were independent, several measurements (spatial orientation) were carried out on the same screw and limb, so these were considered as dependent or paired observations. Thus, a sample size calculation was performed to determine the number of limbs required to detect a mean of paired differences of 0.5 mm SAA with a known SD of differences of 0.5 mm, at a significance level/α of .05 and a power of 80%. According to the calculation results, at least 11 limbs were required to detect differences between the paired measurements DENI, DEXI, TENI, and TEXI.

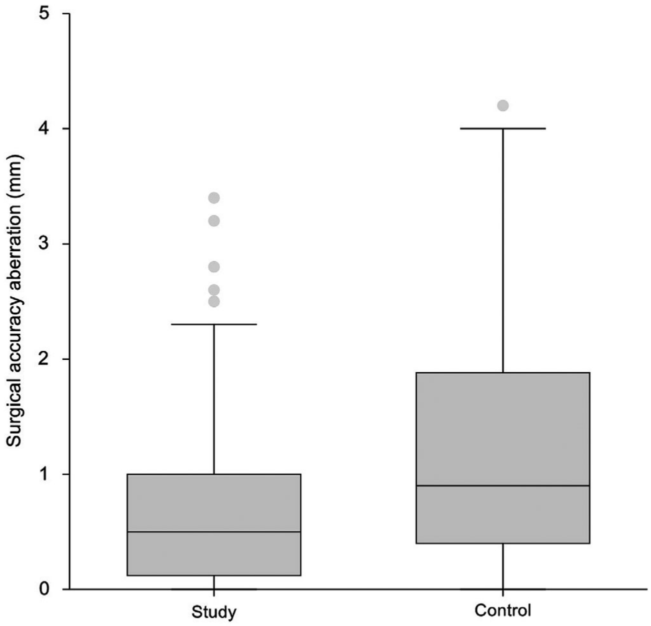

FIGURE 6 Box plots illustrating the distribution of the overall surgical accuracy aberration (in millimeters) in the study group (patient tracker anchored on the purpose-built frame) and in the control group (patient tracker anchored on the dorsal aspect of the proximal phalanx). The whisker boundaries represent 1.5 times the interquartile range (IQR), and the severe outlier boundaries represent three times the IQR. There was a difference between groups (repeated measures of ANOVA, $P = .009$)

2.8 | Statistical analysis

Collected data were analyzed in NCSS 12 statistical software (2018; NCSS, Kaysville, Utah). The overall SAA were illustrated with box plots. Descriptive statistics were performed to compare SAA measurements (overall, DENI, TENI, DEXI, and TEXI) between the study group and the control group. Normality of the outcome variable distribution was tested by using Shapiro–Wilk and Kolmogorov–Smirnov tests. For variables that were not normally distributed, the logarithmic transformation was used. Differences for SAA and for each DENI, TENI, DEXI, and TEXI between the study group and the control group were determined by using a mixed regression model (repeated-measures analysis of variance [ANOVA]) with limb as the subject variable, the group as the between factor variable, and orientation or interference as the within factor variable. Furthermore, the number of measurements smaller than 1, 2, and 3 mm , were calculated in both groups, and differences in proportions between groups were compared by using the χ^2 test. The significance level was set at $\alpha = .05$. Data are reported as mean ± SD.

TABLE 1 The distribution of all drill tract SSA measurements[a]

	Study group				Control group			
SAA	**DENI**	**TENI[b]**	**DEXI**	**TEXI[b]**	**DENI**	**TENI**	**DEXI**	**TEXI**
Mean	0.8	0.6	0.9	0.6	1.2	1.0	1.6	1.1
SD	0.6	0.7	0.9	0.7	1.1	0.7	1.3	0.9
Lower 95% CL mean	0.6	0.3	0.6	0.4	0.8	0.7	1.1	0.8
Upper 95% CL mean	1.0	0.8	1.2	0.8	1.5	1.2	2.0	1.4
Median	0.8	0.4	0.6	0.4	0.9	0.8	1.6	0.9
Minimum	0	0	0	0	0	0	0	0
Maximum	2.2	3.4	2.8	3.2	4.2	3.2	4	3.9

Note: Values are in millimeters.

Abbreviations: CL, confidence level; DENI, dorsal entry imprecision; DEXI, dorsal exit imprecision; SAA, surgical accuracy aberration; TENI, transversal entry imprecision; TEXI, transversal exit imprecision.

[a]On the dorsal and transverse plane at the entry and exit points for the study (patient tracker anchored on the purpose-built frame) and the control group (patient tracker anchored directly on the proximal phalanx), respectively. Note the maximum SAA in both groups.

[b]Not normally distributed.

3 | RESULTS

Twenty-four paired limbs (14 thoracic and 10 pelvic limbs) were obtained from seven horses, including four warmbloods, one Franche-Montagne horse, one Arabian, and one Welsh pony, with ages ranging from 10 to 18 years and body weights ranging from 382 to 618 kg.

In total, 36 screws were placed in each group (12 limbs per group, three screw orientations per limb), resulting in 72 screws placed in total. The virtual and actual position of the SHS corresponded in all measurements carried out, confirming a stable tracker array fixation for both groups.

Interference of the drill with the tracker occurred exclusively in the control (bone) group. This was recorded in 11 of 12 limbs and for 14 of 36 screws placed in the control group and prompted exchange of the short drill bit with a longer drill bit in 10 of 36 screws. Furthermore, in three of 12 limbs in which interference between drill and tracker were recorded, this problem was not resolved with a longer drill bit, and the tracker frame was adjusted.

The overall SAA was not normally distributed, so the log-transformed value was used. The mean overall SAA was lower in the study group (0.7 mm; median, 0.5) than in the control group (1.2 mm; median, 0.9; repeated measures of ANOVA, P = .009; Figure 6) as was the maximum SAA, which was 3.4 mm in the study group and 4.2 mm in the control group (Figure 6).

In each group, a total of 144 measurements was made (DENI, DEXI, TENI, and TEXI determined for each of the 36 screws). The SAA was less than 1 mm in 109 of 144 measurements in the study group and in 78 of 144 measurements in the control group. For all comparisons and tested cutoff values, the proportion of measurements below the cutoff was lower in the study group than in the control group (1 mm: 109/144 vs 78/144, P = .0002; 2 mm: 135/144 vs 114/144, P = .0006; 3 mm: 142/144 vs 134/144, P = .039). Furthermore, the mean SAA was lower than 1 mm for all measurements (DENI, DEXI, TENI, TEXI) of the study group (Table 1); the highest mean value was DEXI (0.9 ± 0.9 mm). The mean value of DEXI was also the highest in the control group (1.6 ± 1.3 mm). There was a notable difference in mean SAA between both groups for TENI (P = .009) and TEXI (P = .026). There was a trend for increased SAA for DEXI (P = .06). However, there was no difference in mean DENI (P = .145) between groups. Neither screw orientation nor the occurrence of interference nor the use of a longer drill bit were found to result in a loss of surgical accuracy.

4 | DISCUSSION

The use of the described purpose-built frame for CAOS consistently resulted in precisely positioned drill tracts in equine cadaveric limbs, with a mean overall SAA of 0.7 mm and a maximum SAA of 3.4 mm as assessed with the StealthMerge and the StealthStation measuring function. This corresponds with system specifications provided by the manufacturer of the StealthStation, which specify the system's surgical accuracy expected in human surgical theatres.[17] Furthermore, the experiments confirmed a stable fixation of the extremity within the frame because fiducial localisation errors were not detected thoroughout the experiments.

Navigation systems used for CAOS mainly serve to orientate the surgeon in the operating field, and a robust relative accuracy in the range of 1 mm is generally accepted.[20] Although computer-assisted surgery is more precise than the conventional techniques, it is still subject to errors.[11,21] Nonetheless, surgical accuracy represents the outstanding criterion for navigation systems.[22-24] On the basis of the data provided by the manufacturer,[17] the authors expected the mean SAA to be in the close range of 2 mm, and most (135/144) individual measurements in the study group ranged within this cutoff value. However, clinical implications of outliers must be considered, even if the presented setup is widely meeting the standards in precision required in equine orthopedic surgery.

In addition to an instable fixation of the equine extremity within the frame, plastic deformation of the frame construct or the navigated instrumentation are potential sources for SAA. Plastic deformation of the navigated instrumentation, mainly due to bending of long drill bits, is likely to occur when one is working on hard cortical bone. In human CAOS, this is a known phenomenon when one is drilling through an area of sclerotic bone.[25] In equine CAOS, the risk of plastic drill bit deformation is certainly potentiated by the thick and dense cortical bone. Therefore, the operating surgeon should choose short drill bits whenever possible and avoid placing excessive pressure on the drill to prevent drill bit bending during the drilling procedure.

Other factors contributing to SAA have been identified for CAOS applications in man. These include instable fixation of the tracker on a target bone of reduced density, for instance, when one is operating on osteoporotic bone of geriatric patients.[25,26] In addition, technical issues inherent to the use of an optical tracking system, such as malfunction of the navigation system with blood contaminated reflectors, can lead to SAA.[25] In the present cadaveric limb study, when extremities without bone pathology were used, the influence of these potential risk factors was not assessed.

The setup involving the purpose-built frame outperformed the conventional tracker array in surgical accuracy. A possible explanation for the lower accuracy observed with the conventional tracker array could be the frequent occurrence of spatial interferences when drilling is performed in close proximity to the tracker. Such spatial interferences can be due to direct physical contact between drill and patient tracker, due to superimposition of instrument and patient tracker (Figure 4), or because the reflecting spheres of the patient or instrument tracker are temporarily obscured by the surgeon from being detected by the localizer camera. This may especially be true when small target structures are being surgically treated, in small operating fields, or in target structures deeply embedded in soft tissues. Under the described circumstances, the detrimental effects on surgical accuracy are compounded when the tracker becomes accidently displaced by the surgeon's hands or surgical instruments or because the tracker is not adequately secured to the target bone.[27,28] Results of the statistical analyses of the present study, however, did not provide evidence of a significant impact on surgical accuracy in the cases with observed spatial interference. Nonetheless, the study reported here provides evidence that spatial interferences are effectively avoided with the use of the purpose-built frame.

According to the authors' clinical experiences, interference of the tracker array and the navigated instruments frequently occurs in CAOS in horses, especially when work is being performed with a conventional setup on the short equine phalangeal bones. Rigid stabilization and artificial expansion of the target structure, as achieved with the proposed purpose-built frame, is a simple yet effective means of avoiding this problem. This becomes even more relevant when work is performed on multiple, articulated target bones, for instance in arthroplasties, arthrodeses, or interventions on the spine and vertebral bodies. In theory, both articulating bones would have to be equipped with a separate tracker, which is commonly done in computer-assisted total knee arthroplasty procedures in man, in which bone trackers are fixed on both tibia and femur.[28,29] However, as long as both articulating bones remain in a stable position relative to each other and the frame, the number of trackers can be effectively reduced while maintaining surgical accuracy. Furthermore, when a frame construct is used, the trackers can be secured in a strategically advantageous position. This is highly relevant for CAOS interventions involving the distal extremity of horses, including the repair of articular fractures or minimally invasive surgical arthrodeses.

The bones that are directly fixed against the solid contact points of the purpose-built frame are the least likely to move in relation to the reference frame construct. The P1 was chosen as the target bone for this study because it was not directly fixed to the pillars of the purpose-built frame. The authors assumed that forceful surgical manipulations, such as applying pressure or traction in any direction to the target bone, could alter its position in relation to the purpose-built frame and the tracker attached to it and ultimately lead to SAA. Similarly, we could have chosen the middle phalanx (P2) as the target bone. However, because P2 is much shorter than P1, it would have been impossible to attach the tracker directly on the target bone and leave enough space for navigated screw placement at three different levels in the control group. This also illustrates the practical advantages and implications of the proposed-built frame for clinical CAOS applications in horses; it facilitates accurate, navigated screw placement in small bones like P2 or across articulations of the distal phalangeal bones without the requirement of directly anchoring the tracker on the target structures.

In equine fracture repair, minimally invasive approaches and short surgical times are important to reduce animal morbidity.[30] This is particularly important when one is operating on the distal extremity with minimal soft tissue coverage to reduce the risks of surgical site infection. Although placing pins to anchor the tracker is not a very invasive procedure, it has been associated with complications, such as injury of neurovascular structures,[31] pin-track infection,[32] or pinhole fractures.[31,33-35] These risks can be minimized by the use of smaller diameter self-tapping and self-drilling 3.2-mm diameter anchoring pins,[31,34] which were used in the present study. Complications arising from pin placement to anchor the tracker are invariably avoided with the use of a purpose-built frame.

The study design focused primarily on identifying differences in surgical accuracy and potential sources for SAA when a purpose-built frame is used compared with the conventional tracker array for CAOS. A meaningful comparison of preparation times for CAOS between the study and the control group could not be achieved because limbs were placed in the purpose-built frame in both groups to provide similar conditions for the drilling procedure. Additional time for placing the pins required only in the control group. However, this is not representative of the clinical situation, in which the operating surgeon chooses to use either the purpose-built frame or the conventional tracker array without applying the purpose-built frame. Nonetheless, our experiences with the purpose-built frame in a clinical setting provide evidence that, in the hands of experienced personnel, the placement of the extremity in the purpose-built frame should add no more than 5 minutes to the overall anesthesia time and does not impede the maintenance of aseptic conditions in the surgical field.

Although the purpose-built frame was designed to facilitate CAOS involving all bones of the equine distal extremity and MCIII/MTIII, this study assessed only surgical accuracy for screw insertion into the proximal phalanx. Nonetheless, only minor modifications are required to provide surgical access to the distal phalanx or navicular bone, such as cutting or drilling a small window into the lateral aspect of the plastic cuff of the NANRIC Ultimate shoe or readjusting the straps over the heel bulbs. These modifications do not seem to compromise the fixation of the distal extremity within the purpose-built-frame. One limitation is that the study population was limited to “normal” sized cadaveric specimens; therefore, extrapolation of the results to foals, miniature breeds, small ponies, or large draught horses is difficult. Additional technical modifications to the frame would be required to accommodate extreme body sizes at both ends of the spectrum.

To the best of the authors' knowledge, this is the first report of an experimental study describing the surgical precision achieved when a CBCT-based surgical navigation system is used for applications in equine orthopedic surgery. In man, this technology has become an integral part of various neurosurgical and orthopedic procedures.[10-11,22-24,29,36] In equine surgery, however, computer-assisted surgery has not yet gained widespread acceptance. At first glance, the high purchase costs for the equipment may seem the most striking explanation. However, the 3D-imaging unit usually is the most expensive part of the investment in a CAOS-ready infrastructure, and many larger equine referral centers already have navigation-compatible 3D-imaging devices at their disposal, and many more are investing in CT units specifically for intraoperative and orthopedic imaging.[37,38] Thus, other factors must be taken into consideration. On the basis of our experiences and the feedback we have received from peers, the most likely explanation is that equine surgeons lack the opportunity to experiment and gain practical experience with CAOS. Only through this exposure will equine surgeons discover the distinct advantages that this technology offers for our discipline, advantages that outweigh reservations such as the disproportionate cost–benefit ratios and the often-reiterated impracticality of CAOS. With increasing access to this technology, the spectrum of indications for CAOS will become closer defined, and more innovative solutions tailored to the special requirements of equine surgery will refine its applications in equine surgical theaters. The purpose-built frame described in this report is a starting point for the refinement of the currently available equipment for CAOS in horses.

In conclusion, the use of a custom-built frame to facilitate CAOS for intervention on proximal P1 meets the high standard in precision required in equine orthopedic surgery. Additional clinical reports and investigations are required to demonstrate the benefits of this technique and its potential application in routine surgical procedures.

ACKNOWLEDGMENTS

Author Contributions: de Preux M, Med Vet: Study design, execution of the experiments, data acquisition, data analysis, and manuscript preparation; Vidondo B, MScBiol, MSc, IT, PhD: Data analysis and writing of the article; Koch C, Dr Med Vet, DACVS, DECVS: Initiated the project, study design, execution of the experiments, data acquisition, data analysis, and manuscript preparation. All authors have read and approved the final version of the article.

The authors thank Etienne de Preux for his support in the development and production of the frame, Vincent de Preux for his help with the graphic illustrations, and Christoph Tschantré for technical support during the study.

CONFLICT OF INTEREST

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

ORCID

Christoph Koch https://orcid.org/0000-0002-4574-6952

REFERENCES

1. Andritzky J, Rossol M, Lischer C, Auer JA. Comparison of computer-assisted surgery with conventional technique for the treatment of axial distal phalanx fractures in horses: an in vitro study. *Vet Surg*. 2005;34(2):120-127.
2. Gygax D, Lischer C, Auer JA. Computer-assisted surgery for screw insertion into the distal sesamoid bone in horses: an in vitro study. *Vet Surg*. 2006;35(7):626-633.
3. Rossol M, Gygax D, Andritzky-Waas J, et al. Comparison of computer assisted surgery with conventional technique for treatment of abaxial distal phalanx fractures in horses: an in vitro study. *Vet Surg*. 2008;37(1):32-42.
4. Auer JA. Principles of fracture treatment. In: Auer JA, Stick JA, eds. *Equine Surgery*. 4th ed. St Louis, MO: Elsevier; 2012:1054.
5. Richardson D. CT guided fracture fixation in the foot. Paper presented at: American College of Veterinary Surgeons Veterinary Symposium; November 1-3, 2012; National Harbor, Maryland.
6. Gasiorowski JC, Richardson DW. Clinical use of computed tomography and surface markers to assist internal fixation within the equine hoof. *Vet Surg*. 2015;44(2):214-222.
7. Jackson MA, Ohlerth S, Furst AE. Use of an aiming device and computed tomography for assisted debridement of subchondral

cystic lesions in the limbs of horses. *Vet Surg*. 2019;48(S1): O15-O24.
8. Colles C. Navicular bone fractures in the horse. *Equine Vet Educ*. 2011;23(5):255-261.
9. Perrin R, Launois T, Brogniez L, et al. The use of computed tomography to assist orthopaedic surgery in 86 horses (2002–2010). *Equine Vet Educ*. 2011;23(6):306-313.
10. Tian NF, Huang QS, Zhou P, et al. Pedicle screw insertion accuracy with different assisted methods: a systematic review and meta-analysis of comparative studies. *Eur Spine J*. 2011;20 (6):846-859.
11. Cheng T, Zhao S, Peng X, Zhang X. Does computer-assisted surgery improve postoperative leg alignment and implant positioning following total knee arthroplasty? A meta-analysis of randomized controlled trials? *Knee Surg Sports Traumatol Arthrosc*. 2012;20(7):1307-1322.
12. Peters KM, Hutter E, Siston RA, Bertran J, Allen MJ. Surgical navigation improves the precision and accuracy of tibial component alignment in canine total knee replacement. *Vet Surg*. 2016;45(1):52-59.
13. Schwarz CS, Rudolph T, Koval JH, Auer JA. Comparison of the VetGate and SurgiGATE 1.0 computer assisted surgery systems for insertion of cortex screws across the distal phalanx in horses: an in vitro study. *Pferdeheilkunde*. 2017;33:120-132.
14. Heer C, Fürst A, Del Chicca F, Jackson MA. Comparison of 3D-assisted surgery and conservative methods for treatment of type III fractures of the distal phalanx in horses. *Equine Vet Educ*. 2020;32(S10):42-51.
15. Schwarz CS, Rudolph T, Koval JH, Auer JA. Introduction of 3.5-mm and 4.5-mm cortex screws into the equine distal sesamoid bone with the help of the VetGate computer assisted surgery systems and comparison of the results with those achieved with the SurgiGATE 1.0 system: an in vitro study. *Pferdeheilkunde*. 2017;33:223-230.
16. de Preux M, Klopfenstein Bregger MD, Brünisholz HP, Van der Vekens E, Schweizer-Gorgas D, Koch C. The clinical use of computer-assisted orthopedic surgery in horses. *Vet Surg*. In press.
17. Medtronic. StealthStation S8 Cranial Optical Kurzhandbuch. *Medtronic Navigation*. Colorado: Louisville; 2019.
18. Sikorski JM, Chauhan S. Computer-assisted orthopaedic surgery: do we need CAOS? *J Bone Joint Surg Br*. 2003;85(3): 319-323.
19. Kozak J, Nesper M, Fischer M, et al. Semiautomated registration using new markers for assessing the accuracy of a navigation system. *Comput Aided Surg*. 2002;7(1):11-24.
20. Strauß G, Hofer M, Korb W, et al. Genauigkeit und Präzision in der Bewertung von chirurgischen Navigations- und Assistenzsystemen [in German. *HNO*. 2006;54(2):78-84.
21. Mavrogenis AF, Savvidou OD, Mimidis G, et al. Computer-assisted navigation in orthopedic surgery. *Orthopedics*. 2013;36 (8):631-642.
22. Schmerber S, Chassat F. Accuracy evaluation of a CAS system: laboratory protocol and results with 6D localizers, and clinical experiences in otorhinolaryngology. *Comput Aided Surg*. 2001;6 (1):1-13.
23. Vorbeck F, Cartellieri M, Ehrenberger K, Imhof H. Experiences in intraoperative computer-aided navigation in ENT sinus surgery with the Aesculap navigation system. *Comput Aided Surg*. 1998;3(6):306-311.
24. Reinhardt H, Trippel M, Westermann B, Gratzl O. Computer aided surgery with special focus on neuronavigation. *Comput Med Imaging Graph*. 1999;23(5):237-244.
25. Bae DK, Song SJ. Computer assisted navigation in knee arthroplasty. *Clin Orthop Surg*. 2011;3(4):259-267.
26. Stockl B, Nogler M, Rosiek R, Fischer M, Krismer M, Kessler O. Navigation improves accuracy of rotational alignment in total knee arthroplasty. *Clin Orthop Relat Res*. 2004; 426:180-186.
27. Mihalko WM, Duquin T, Axelrod JR, Bayers-Thering M, Krackow KA. Effect of one- and two-pin reference anchoring systems on marker stability during total knee arthroplasty computer navigation. *Comput Aided Surg*. 2006;11(2):93-98.
28. Casper M, Mitra R, Khare R, et al. Accuracy assessment of a novel image-free handheld robot for total knee arthroplasty in a cadaveric study. *Comput Assist Surg (Abingdon)*. 2018;23(1): 14-20.
29. Amanatullah DF, Burrus MT, Sathappan SS, Levine B, Di Cesare PE. Applying computer-assisted navigation techniques to total hip and knee arthroplasty. *Am J Orthop (Belle Mead NJ)*. 2011;40(8):419-426.
30. Ahern B. Surgical site infection and the use of antimicrobials. In: Auer JA, Stick JA, eds. *Equine Surgery*. 4th ed. St Louis: MO; 2012:74.
31. Li CH, Chen TH, Su YP, Shao PC, Lee KS, Chen WM. Periprosthetic femoral supracondylar fracture after total knee arthroplasty with navigation system. *J Arthroplasty*. 2008;23(2): 304-307.
32. Sikorski JM, Blythe MC. Learning the vagaries of computer-assisted total knee replacement. *J Bone Joint Surg Br*. 2005;87 (7):903-910.
33. Bonutti P, Dethmers D, Stiehl JB. Case report: femoral shaft fracture resulting from femoral tracker placement in navigated TKA. *Clin Orthop Relat Res*. 2008;466(6):1499-1502.
34. Hoke D, Jafari SM, Orozco F, Ong A. Tibial shaft stress fractures resulting from placement of navigation tracker pins. *J Arthroplasty*. 2011;26(3):504.e5-504.e8.
35. Jung KA, Lee SC, Ahn NK, Song MB, Nam CH, Shon OJ. Delayed femoral fracture through a tracker pin site after navigated total knee arthroplasty. *J Arthroplasty*. 2011;26(3):505.e9-505.e11.
36. Lee DJ, Kim SB, Rosenthal P, Panchal RR, Kim KD. Stereotactic guidance for navigated percutaneous sacroiliac joint fusion. *J Biomed Res*. 2016;30(2):162-167.
37. Richardson DW. The tao of equine fracture repair. Milne Lecture. In: Proceedings from the American Association of Equine Practitioners; December 7-11, 2019; Denver CO.
38. Riggs CM. Computed tomography in equine orthopaedics—the next great leap? *Equine Vet Educ*. 2019;31(3):151-153.

How to cite this article: de Preux M, Vidondo B, Koch C. Influence of a purpose-built frame on the accuracy of computer-assisted orthopedic surgery of equine extremities. *Veterinary Surgery*. 2020;49: 1367–1377. https://doi.org/10.1111/vsu.13484