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CLINICAL RESEARCH

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# Effect of screw insertion angle and speed on the incidence of transcortical fracture development in a canine tibial diaphyseal model

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## Abstract

**Objective:** To assess the incidence of transcortical fracture (TCF) development based on screw insertion angle and screw insertion speed.

**Study design:** Cadaveric experimental study.

**Sample population:** Sixty-six canine tibiae.

**Methods:** Sixty-six cadaveric tibiae were randomly assigned to one of six groups that varied based on screw insertion angle relative to the pilot hole (0, 5, or 10°) and screw insertion speed (650 or 1350 revolutions per minute [rpm]). Each tibia was mounted in a custom jig. Locking self-tapping screws (3.5 mm) were inserted at varying speeds and insertion angles, based on group assignment. Orthogonal radiographs were evaluated for TCFs. Fisher's exact tests with a Bonferroni correction were performed to evaluate differences in the frequency of TCF between groups.

**Results:** In Group A (0°/650 rpm: control), a 0% TCF rate was observed ($n = 0/80$). Group B (5°/650 rpm) had a 3.75% TCF rate ($n = 3/80$). Group C (10°/650 rpm) had a 12.5% TCF rate ($n = 10/80$). Group D (10°/hand insertion) had a 3.75% TCF rate ($n = 3/80$). Group E (10°/1350 rpm) had a 17.5% TCF rate ($n = 14/80$). Group F (0°/1350 rpm) had a 0% TCF rate ($n = 0/80$). Groups C and E had the highest TCF rates with a difference in TCF rates observed between the control group and Group C ($p = .001$) and between the control group and Group E ($p < .001$).

**Conclusion:** Increased screw insertion angle and insertion speed appear to be predisposing factors for TCF development in cadaveric bone.

**Clinical significance:** Ensuring screw insertion is coaxial with the pilot hole and using slower screw insertion speeds may help reduce the risk of TCF development.

**Abbreviations:** rpm, revolutions per minute; STS, self-tapping screw; TCF, transcortical fracture.

  

# 1 | INTRODUCTION

Bone screws are one of the most widely used implants in human and veterinary orthopedics.[1–4] They can be used as a sole means of stabilization or may be used in conjunction with other orthopedic implants such as bone plates.[1–4] Numerous adaptations and modifications to screw design have been made to maximize screw effectiveness for specific applications.[1–4] Conventional bone screws have a conical tip and use of a tap is required to cut threads in the bone before screw insertion. By comparison, self-tapping screws (STS) are equipped with cutting flutes on the tip of the screw that allow the screw to cut its own threads during screw insertion, eliminating the need to tap threads in the bone for the screw.[1–8] By eliminating a step in screw insertion the use of STS can decrease surgical operating time and length of general anesthesia, potentially reducing the risk of complications such as surgical site infection.[1,3–6]

Prior studies on the use of STS have examined various aspects of screw design that aim to optimize screw performance such as length and number of cutting flutes, screw insertion torque and pullout strength.[3,5–8] Screws with longer cutting flutes and greater number of cutting flutes have been shown to have decreased insertional torque compared to screws with shorter cutting flutes and fewer number of cutting flutes, decreasing the risk of screw failure during insertion and iatrogenic damage to the bone.[3] However, screws with longer cutting flutes require a longer overall screw length to fully engage the transcortex as the fully threaded portion of the screw must engage the transcortex to provide the greatest construct stability and pullout strength.[3,5,6]

The use of STS does speed up the surgical procedure but it can also result in increased rates of certain complications such as transcortical fractures (TCF).[1] Transcortical fractures are defined as fractures of the transcortex that develop during the process of screw application and are identifiable on radiographs as saucer-shaped radiolucent defects of the transcortex.[1] A previous study by Boekhout et al. examined the incidence of TCF associated with cortical STS in dogs following TPLO surgery.[1] The incidence of TCF was higher ($p = .006$) with the use of cortical STS (18%) compared to cortical non-STS screws (0.8%).[1] They hypothesized that the mechanism of TCF development was related to the buildup of bone debris in the relatively short cutting flutes of the STS, impairing the efficacy of the cutting apparatus.

The thread profile of locking screws differs to that seen with cortical screws, having finer thread pitch and depth.[9] Despite these differences, no studies to date have evaluated factors contributing to TCF development when locking STS are used. The goal of the current study was thus to evaluate potential contributing factors for TCF development in a canine tibial diaphyseal model. Our first null hypothesis is that there will be no difference in TCF rate based on screw insertion angle. Our second null hypothesis is that there will be no difference in TCF rate based on screw insertion speed.

# 2 | MATERIALS AND METHODS

## 2.1 | Tibial diaphyseal model

A total of 66 tibiae from 39 cadaveric dogs with bodyweights ranging from 20.5 to 36.9 kg, which were sourced from a local humane society and were euthanized for reasons unrelated to the study, were collected. Only tibiae from skeletally mature dogs (tibiae with closed physes based on radiographic assessment) were included and those with any underlying orthopedic pathology (tibial fractures, synostosis of the tibia and fibula) were excluded from the study. The cadavers were promptly frozen following euthanasia and were thawed for 48 h prior to use in the study. Specimens were then prepared for use in the study by dissecting the fibula and all soft tissues from each tibia. Each individual tibia was labeled with a unique identifier and a random number generator (Excel, Microsoft Corporation, Redmond, Washington) was used to assign each tibia randomly to one of six groups, which varied based on screw insertion angle in degrees (°) relative to the pilot hole and screw insertion speed in revolutions per minute (rpm): Group A: 0°/650 rpm; Group B: 5°/650 rpm; Group C: 10°/650 rpm; Group D: 10°/screws placed manually with handheld screwdriver; Group E: 10°/1350 rpm; Group F: 0°/1350 rpm. The different screw insertion speeds were chosen to emulate the speed settings found on a commercially available orthopedic drill (DeSoutter V-Drive).[10] Angles of insertion were chosen to best reflect what we thought would be a reasonable error (up to 10° off axis) to expect in the clinical setting.[11,12] For the purposes of this study, the tibial diaphysis was defined as the portion of bone comprising the middle 70% of the length of the tibia.

## 2.2 | Tibial fixation jig application and experimental apparatus

A custom-built tibial fixation jig was used to hold the tibiae in a fixed position for application of the bone plate and screws (Figure 1). The jig consisted of a wooden platform to which two pairs of "L" brackets were attached, each pair connected by a large external skeletal fixator (ESF) carbon fiber rod (IMEX Veterinary Inc., Longview, Texas). The tibia was fixed in the jig by two 3/16-inch bolts, one inserted through the proximal metaphysis and

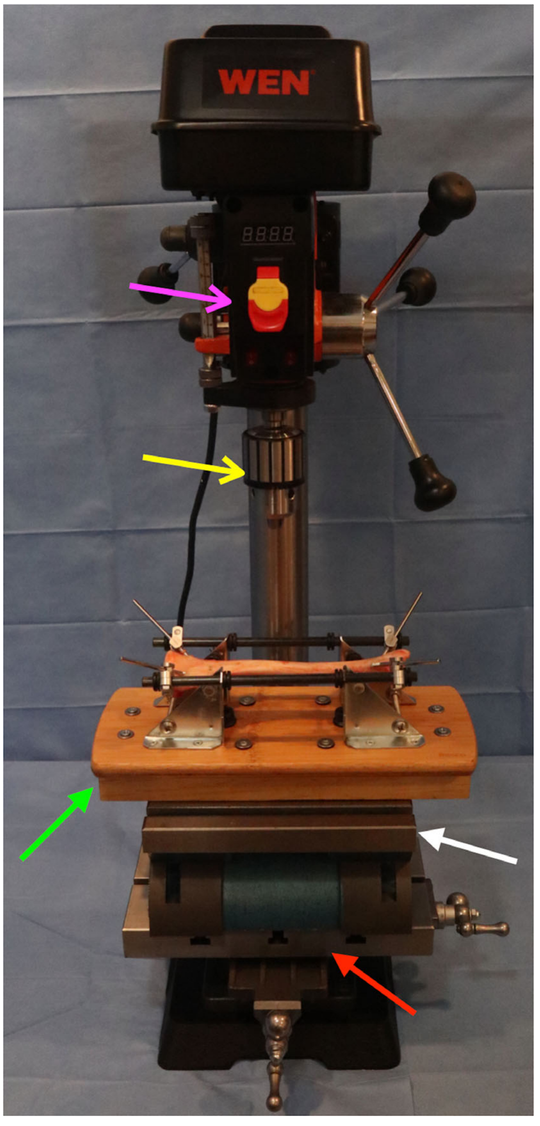


FIGURE 1 Testing apparatus setup. The tibial fixation jig (green arrow) was attached to a milling tilt table (white arrow), which allowed the tibia to be rotated about its long axis. This was mounted on a cross-slide XY table (red arrow), which allowed the tibia to be moved so that the spindle (yellow arrow) could be positioned directly over the plate hole of interest. Once assembled, this testing apparatus was mounted on a 12-inch variable speed bench top drill press (magenta arrow).

the other inserted through the distal metaphysis, both in the sagittal plane, as well as by four 4.0 mm Duraface ESF end-threaded pins (IMEX Veterinary Inc.), two inserted in the proximal metaphysis and two inserted in the distal metaphysis. The bolts through the tibia were secured directly to the "L" brackets and the Duraface pins were connected to the carbon fiber rods using large SK single clamps (IMEX Veterinary Inc.). Each tibia was oriented in the jig with the medial aspect of the tibia facing upwards. Orthogonal radiographs, consisting of one mediolateral and one craniocaudal projection of each tibia were taken after fixation in the jig and prior to plate and screw application using a Poskom VET 20-BT portable X-ray unit (VUE Imaging, San Luis Obispo, California). The diaphyseal diameter of each tibia was measured from the craniocaudal radiograph at the level of the tibial isthmus using a digital image templating program (vPOP Pro, VetSOS Education Ltd., Shrewsbury, United Kingdom).

The tibial fixation jig was affixed to a 7 × 10-inch milling tilt table (Grizzly Industrial, Bellingham, Washington), which allowed for rotation of the tibiae about the tibial long axis. The tilt table was affixed to a 6 × 12-inch cross-slide XY table (Palmgren, Naperville, Illinois) allowing for horizontal translation of the tibiae underneath the spindle. This setup was mounted on a 12-inch variable speed benchtop drill press (WEN, West Dundee, Illinois), forming the complete experimental apparatus (Figure 1). A digital angle gauge (Klein Tools, Lincolnshire, Illinois) that was accurate to ±0.2° was used to confirm the orientation of the experimental apparatus. The base of the tibial fixation jig was leveled to 0.0° and fixed in position. The spindle of the drill press was positioned using the digital angle gauge to ensure that the spindle was perpendicular to the base of the tibial fixation jig, thereby ensuring accurate drilling and screw placement.

## 2.3 | Bone plate application

A 3.5 mm combination double threaded, locking, low-contact narrow compression plate (Veterinary Orthopedic Implants, St. Augustine, Florida) was placed on the medial aspect of the tibial diaphysis and was centered in the cranial to caudal middle of the diaphysis. The length of the plate used (8 hole or 10 hole) was determined based on the overall length of the tibia to ensure drilling and screw application occurred in diaphyseal bone. The plate was temporarily affixed to the bone with two 0.062-inch k-wires placed through the temporary fixation holes in the plate. The position of the plate was adjusted with the aid of a spirit level (Milwaukee Tools, Brookfield, Wisconsin) until the plate was parallel with the base of the tibial fixation jig (Figure 2A). A bicortical locking STS was placed in the most proximal plate hole and in the most distal plate hole to secure the plate to the bone using a standard screw insertion technique.[13]

A random number generator (Excel) was used to determine the order of drilling and screw insertion for the remaining plate holes. For each plate hole, a 2.8 mm locking drill guide was threaded into the plate hole. A 2.8 mm drill bit was mounted on the spindle of the drill press and the drill press was set to run at 1350 rpm, the maximum drill speed of a commercially available

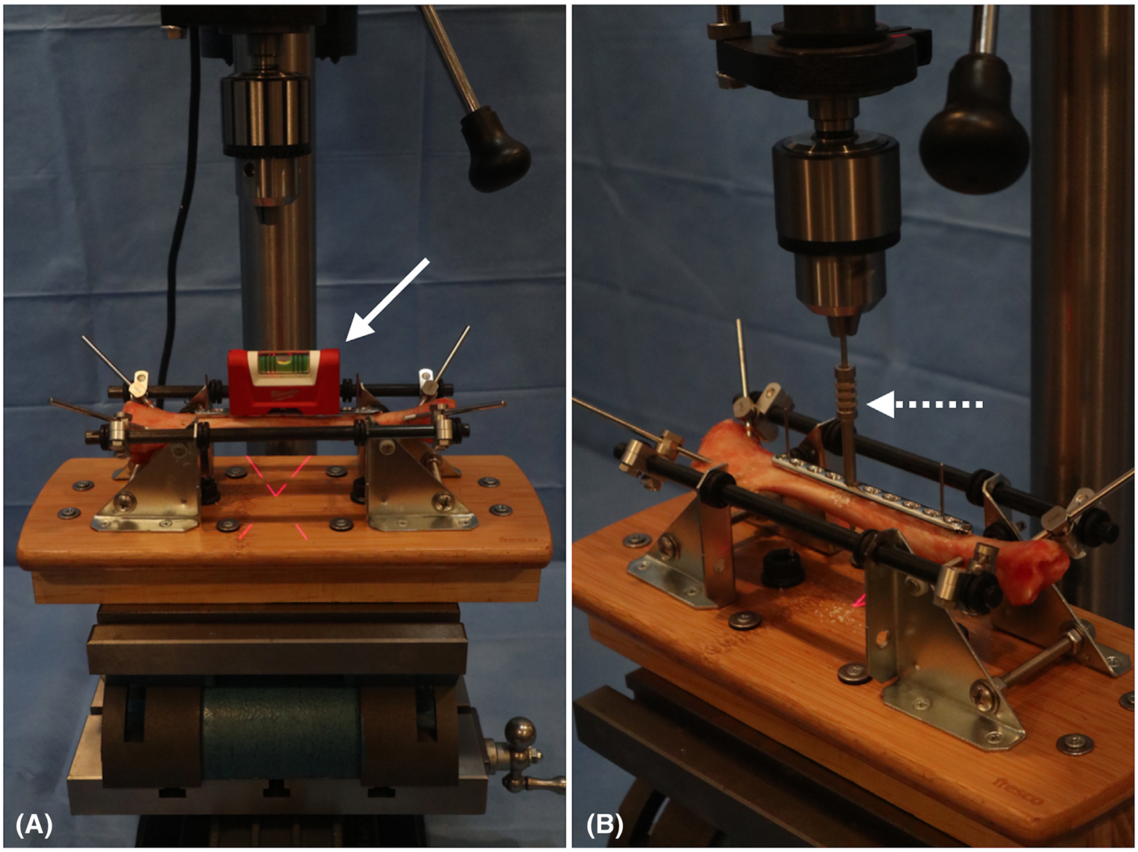


FIGURE 2 (A) A spirit level (solid white arrow) was used to position the plate parallel to the base of the tibial fixation jig, as it was secured to the tibia. (B) This ensured that the spindle, and thus the drill bit, were perpendicular to the plate, allowing on-axis drilling of the pilot holes through the locking drill guide (dashed white arrow).

veterinary orthopedic drill (DeSoutter V-Drive VMBQ-708).[10] The drill bit was advanced through the drill guide and a pilot hole was drilled through both cortices of the tibial diaphysis (Figure 2B). This drilling procedure was repeated for all holes in the plate based on the order determined by random assignment. To rule out any iatrogenic damage to the bone associated with drilling the pilot holes, orthogonal radiographs of the tibia mounted to the tibial fixation jig were taken prior to screw insertion.

## 2.4 | Screw insertion with drill press (group A–group C, group E–group F)

Tibiae were rotated in the axial plane (0, 5 or 10°) based on the previous randomized group assignment by rotating the tilt table top 0, 5 or 10° and using the digital angle gauge to confirm the degree of rotation (Figure 3A–C). Locking STS (3.5 mm thread diameter, 2.9 mm core diameter, 0.8 mm thread pitch) were applied using a T15 stardrive driver mounted on the drill press set to run at 650 rpm (Group A–Group C) or 1350 rpm (Group E and Group F). The insertion speeds were selected to match the maximum rpm and the screw-insertion rpm found in a commonly used veterinary orthopedic drill (DeSoutter V-Drive VMBQ-708).[13] All screws used in this study were 30 mm in length to ensure bicortical screw purchase. Screws were inserted past the transcortex until the head of the screw was just above the level of the plate top. A hand-held T15 screwdriver was then used to tighten the screws manually until the screw head fully engaged the locking plate. Screw placement was repeated for all holes in the plate based on the order determined by random assignment. For each individual tibia, all screws were inserted at the same angulation (0, 5 or 10°) relative to the pilot hole and at the same speed (650 rpm or 1350 rpm), based on the previous randomized tibia group assignment.

## 2.5 | Screw insertion by hand (Group D)

The tilt table was set to an angle of 10° to rotate the tibia 10° axially around the long axis and the degree

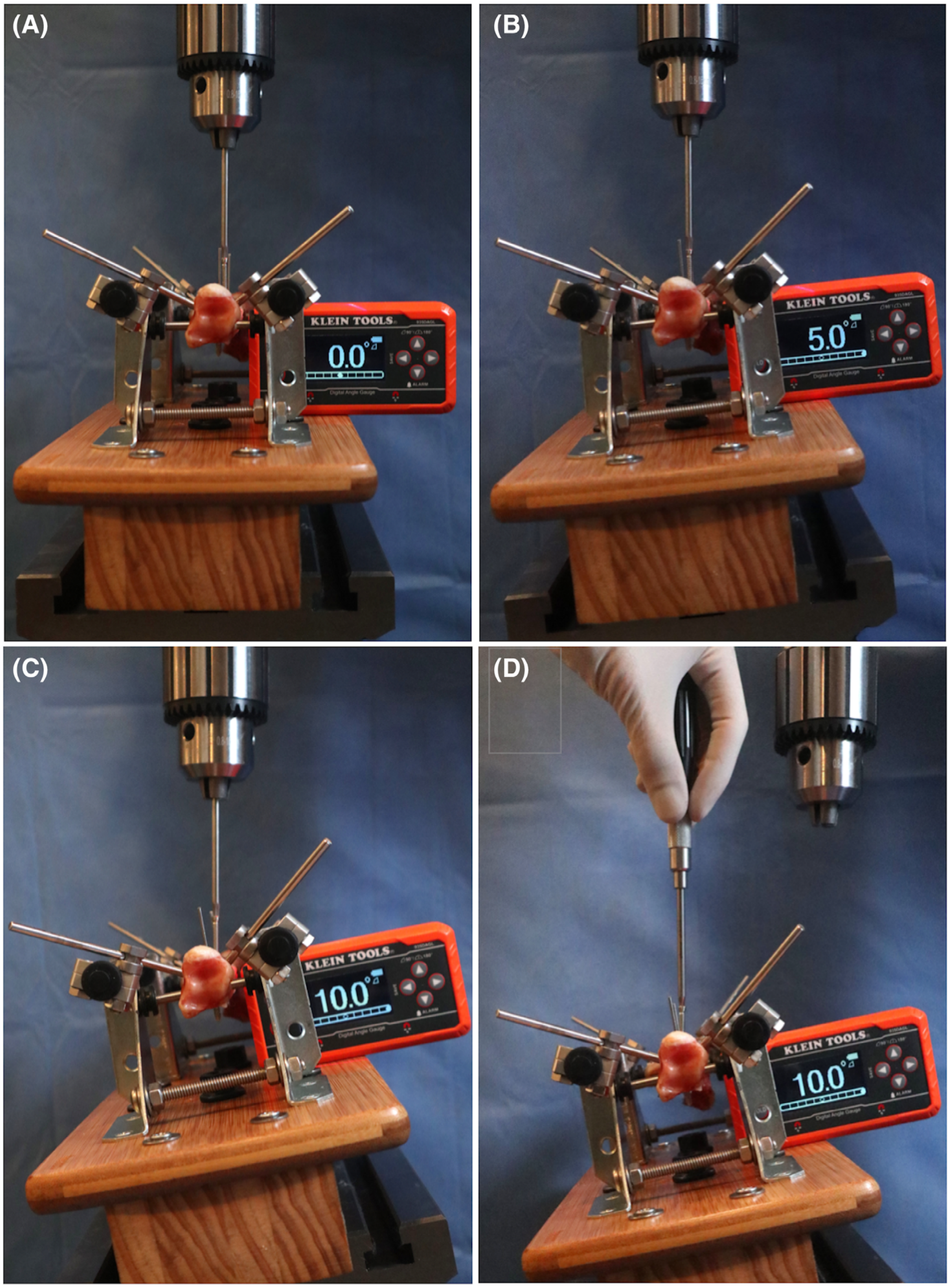


FIGURE 3 Following the creation of all the pilot drill holes, screws were inserted: (A) coaxial to the drill tract (groups A and F); (B) after 5° axial tibial rotation (group B), (C) after 10° axial tibial rotation (screws inserted by power: groups C and E) and (D) after 10° axial tibial rotation (screws inserted by hand: group D).

of rotation was confirmed with a digital angle gauge. A handheld T15 screwdriver was used to insert 3.5 mm locking STS into the bone (Figure 3D). The screwdriver was first orientated so that the long axis of the screwdriver shaft was positioned perpendicular to the horizontal plane and the screwdriver position was confirmed using a digital angle gauge. Locking STS (3.5 mm) were then inserted sequentially into each plate hole following the previously determined random hole assignment using the handheld T15 screwdriver until the screw heads fully engaged the plate holes.

### 2.6 | Transcortical fracture identification

After screw insertion was complete for each individual tibia, the temporary fixation pins were removed. The tibia was removed from the jig and orthogonal radiographs of the tibia were then taken, consisting of 1 mediolateral radiograph and 1 craniocaudal radiograph. Each tibia was inspected radiographically for evidence of TCF (Figure 4). One observer (a board-certified surgeon) who was blinded to the method of screw insertion (SCJ) was tasked with identifying the number of TCF for each tibia.

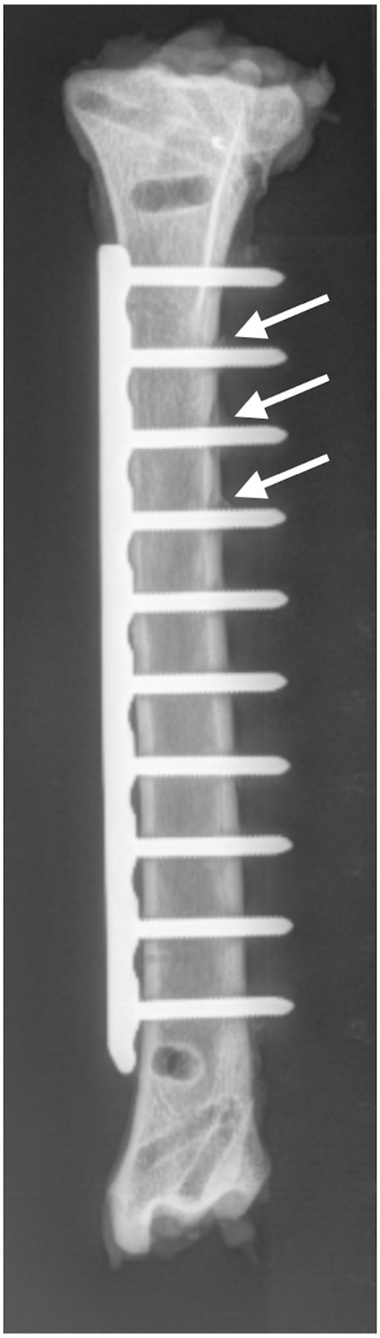

FIGURE 4 Cranio-caudal radiograph of a tibia from group E (10°/1350 rpm) demonstrating three transcortical fractures (white arrows).

Tibiae that developed fissure fractures during drilling or screw placement were excluded from the study.

### 2.7 | Statistical analysis

Results of a power analysis performed on initial pilot screw insertion of 19 specimens suggested that a minimum of 80 samples per group would be required to demonstrate significant differences with an alpha of .05 and a beta of .8. Based on this power analysis, 80 screws were included in each group. Specimen bodyweights and tibial diaphyseal diameters were compared between groups using a one-way ANOVA. The number of TCF in each of the six groups was determined and the TCF rate was calculated for each group. Statistical analyses were performed using a commercially available statistical software package (Sigmaplot 15, Inpixon, San Jose, California). For the purposes of this study, Group A (0°/650rpm) served as the control group against which all other groups were compared. Each study group (Group B–Group F) was individually compared to the control group (Group A) using a Fisher's exact test to determine if a significant difference in TCF rates between groups was present. A Bonferroni correction was performed to adjust the $p$ value to account for multiple comparisons. This correction decreased the $p$ value for determining significance from the initially selected value of $p \leq .05$ to a value of $p \leq .01$.

## 3 | RESULTS

All data regarding dog weight and tibial diaphyseal diameter for tibial specimens in each group are summarized in Table 1. No differences in mean dog bodyweight ($p = .79$) or mean tibial diaphyseal bone diameter ($p = .63$) were identified between groups (Table 1). No cis- or transcortical fractures were identified in any tibia after drilling the pilot holes. No cis-cortical fractures were identified in any bone after the screws were placed. One tibia from Group E developed a fissure fracture during screw application and was excluded from the study. All TCF data and results are summarized in Table 2. In Group A, no TCF were observed out of 80 screws inserted at a 0° screw insertion angle at 650 rpm (0% TCF rate). In Group B, 3 TCF were observed out of 80 screws inserted at a 5° screw insertion angle at 650 rpm (3.75% TCF rate). In Group C, 10 TCF were observed out of 80 screws inserted at a 10° screw insertion angle at 650 rpm (12.5% TCF rate). In Group D, 3 TCF were observed out of 80 screws inserted at a 10° screw insertion angle with a handheld screwdriver (3.75% TCF rate). In Group E, 14 TCF were observed out of 80 screws inserted at a 10° screw insertion angle at 1350 rpm (17.5% TCF rate). In Group F, no TCF were observed out of 80 screws inserted at a 0° screw insertion angle at 1350 rpm (0% TCF rate). Groups C and E had the overall highest TCF rates with significantly higher TCF rates observed between the control group and Group C ($p = .001$) and between the control group and Group E ($p < .001$). No difference in TCF rates was identified between Groups A and B ($p = .245$),

**TABLE 1** Summary of cadaveric dog weight and tibial diaphyseal diameter based on tibial group assignment. Mean dog bodyweight and mean diaphyseal diameter were compared between groups using a one-way ANOVA. No differences in mean bodyweight ($p = .79$) or mean diaphyseal diameter ($p = .63$) were detected between groups.

| Group | Mean dog weight (kg) | Standard deviation weight | Mean diaphyseal diameter (mm) | Standard deviation diaphyseal diameter |
|---|---|---|---|---|
| A (control) | 29.0 | 5.5 | 15.1 | 1.01 |
| B | 28.4 | 5.5 | 14.9 | 0.66 |
| C | 28.2 | 6.2 | 15.3 | 1.02 |
| D | 28.7 | 5.5 | 15.2 | 1.62 |
| E | 28.8 | 5.8 | 14.5 | 0.97 |
| F | 31.2 | 2.6 | 15.0 | 1.10 |

**TABLE 2** Screw insertion data based on tibia group assignment.

| Group | Insertion speed (rpm) | Insertion angle (°) | Number of screws | Number of TCF | TCF rate (%) | Fisher's exact test *p* |
|---|---|---|---|---|---|---|
| A (control) | 650 | 0 | 80 | 0 | 0 | N/A |
| B | 650 | 5 | 80 | 3 | 3.75 | 0.245 |
| C | 650 | 10 | 80 | 10 | 12.5 | 0.001 |
| D | Manual | 10 | 80 | 3 | 3.75 | 0.245 |
| E | 1350 | 10 | 80 | 14 | 17.5 | <0.001 |
| F | 1350 | 0 | 80 | 0 | 0 | N/A |

between Groups A and D ($p = .245$) or between Groups A and F (no TCF in either group—test not performed).

## 4 | DISCUSSION

We demonstrated that increased screw insertion angle relative to the pilot hole was associated with an increased TCF rate. An increase in TCF rate was observed in Group C (10° screw insertion angle, 650 rpm) ($p = .001$) and Group E (10° screw insertion angle, 1350 rpm) ($p < .001$) when compared to the control group. The TCF rate for Group B (5° screw insertion angle, 650 rpm) was higher than the control group (3.75% vs. 0%, respectively) but it was not significantly different ($p = .245$). We therefore do not accept our first null hypothesis. Increased screw insertion speed was not associated with increased TCF development when screw insertion was coaxial with the pilot hole as no TCF were observed in the control group (0° screw insertion angle, 650 rpm) or in Group F (0° screw insertion angle, 1350 rpm). However, when the screws were inserted off-axis to the pilot hole, increased screw insertion speed was associated with an increased TCF rate. When inserting screws at 10°, hand insertion (low speed) had the lowest TCF rate (3.75%), power insertion at 650 rpm had a 12.5% TCF rate, and power insertion at 1350 rpm had the highest TCF rate (17.5%). We therefore fail to accept our second null hypothesis.

Based on the results of the current study it appears that both screw insertion angle and screw insertion speed are important factors underlying TCF development when using locking STS. Chief amongst these, screw insertion angle appeared to be the most important contributor to TCF development in this study. Surgeons should take care to ensure that screw insertion angle is coaxial with the pilot hole to reduce the risk of TCF development. We did not evaluate the mechanism by which off-axis screw insertion results in TCF development but we suspect that the tip of the off-axis screw at least partially misses the pilot hole in the transcortex, resulting in the cutting flutes of the screw engaging and inefficiently cutting undrilled bone of the transcortex, and ultimately resulting in the screw pushing on and fracturing through the transcortex as the screw is advanced into the bone. At lower insertion speeds such as those encountered during hand insertion, the screw tip presumably redirects to follow the path of the predrilled pilot hole when initially inserted off axis. At increased insertion speeds however, the screw may be less likely to redirect from its initial insertion angle thereby increasing the risk of TCF development. Interestingly, when a screw is placed coaxial to the pilot hole, screw insertion speed did not appear to increase the rate of TCF development.

The clinical relevance of a TCF likely depends on the location of the TCF on the bone and its position relative to adjacent implants. A common clinical scenario in which TCF may occur is during the performance of a proximal tibial osteotomy, such as a TPLO. In the previous TPLO study by Boekhout et al., all TCF occurred in the distal diaphyseal segment with no metaphyseal TCF identified.[1] A TCF occurring at the most distal end of a TPLO plate for example, could act as a stress riser, potentially later propagating into to a complete tibial fracture when the dog begins to ambulate on the limb, while a TCF occurring in the mid-region of a plate may be protected from propagation into a fracture by the implant and screws proximal and distal to the TCF. Based on the results of this study, in order to help decrease the risk of TCF, the surgeon should ensure that screws are inserted slowly and coaxial to the pilot hole, with consideration given to hand-insertion of screws.

One limitation of this study is that we only assessed the rate of TCF development in the tibia. Cortical bone thickness, bone density, cross-sectional shape of the bone and the diameter of the bone column could all influence the rate of TCF development. The statistical methods used in this study do not account for the possible correlation of TCF to specific tibial specimens or different tibial specimens from the same dog. Future studies should therefore examine TCF rates in various types of long bones to see if TCF rates vary based on the type of long bone assessed. It is also possible that our results may have been influenced by the fact that we used cadaveric bones that were previously frozen. Another limitation to this study is that only one specific type and size of locking STS was evaluated. Future studies should assess the effects that differing locking STS designs and sizes have on TCF rates. Additionally, unlike the experience in the clinical setting, the tibiae in the current study were rigidly secured to a jig before drilling and screw insertion. It is possible that this experimental set up influenced the rates of TCF identified in this study. For example, we cannot rule out the possibility that the tibial constraints in our testing apparatus prevented screws from redirecting, thereby artificially increasing the rate of TCF reported here. Another limitation is that we only included radiographically visible TCF in our results. A visual assessment of the bones for TCF may increase the number of TCF identified.[14] Finally, radiographs were only reviewed by a single blinded observer. Having multiple blinded observers review radiographs for TCF, potentially also including a board-certified radiologist, may have helped reduce any variability in the detection of TCF.

This study provides evidence for some predisposing risk factors underlying TCF development in a cadaveric canine tibial diaphyseal model. Specifically, the findings of our study suggest that the combined effects of off-axis screw insertion relative to the pilot hole and insertion at higher speed have the greatest effects on TCF rate. In the clinical setting, care should be taken to ensure screws are inserted coaxially relative to the pilot hole and slower screw insertion speeds should be utilized potentially to reduce the risk of TCF development.

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**Author Contributions:** Sadowitz PM, DVM: Primary manuscript authorship, study design, specimen collection and preparation, experimental apparatus design, data collection, data assessment. Jones SC, MVB, MS, DACVS, DECVS: Study design, specimen collection, acquisition of supplies, experimental apparatus design, data assessment, manuscript figure design, manuscript review. Beale BS, DVM, DACVS: Project design, data assessment, manuscript review. Cross AR, DVM, DACVS: Project design, data assessment, manuscript review. Hudson CC, DVM, MS, DACVS: Project design, statistical analysis of collected data, data assessment, manuscript review.

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## CONFLICT OF INTEREST STATEMENT

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

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## REFERENCES

1. Boekhout C, Cross A. Incidence of transcortical tibial fractures with self-tapping and non-self-tapping screws in a canine TPLO model. *Vet Surg*. 2012;41(7):898-901.
2. Johnson AL, Houlton JEF, Vannini R. *AO Principles of Fracture Management in the dog and cat*. Thieme; 2007:28-30.
3. Yerby S, Scott CC, Evans NJ, Messing KL, Carter DR. Effect of cutting flute design on cortical bone screw insertion torque and pullout strength. *J Orthop Trauma*. 2001;5:216-221.
4. Bickley MB, Hanel DP. Self-tapping versus standard tapped titanium screw fixation in the upper extremity. *J Hand Surg Am*. 1998;23(2):308-311.
5. Phillips JH, Rahn BA. Comparison of compression and torque measurements of self-tapping and pretapped screws. *Plast Reconstr Surg*. 1989;83(3):447-458.
6. Battula S, Schoenfeld A, Vrabec G, Njus GO. Experimental evaluation of the holding power/stiffness of the self-tapping bone screws in normal and osteoporotic bone material. *Clin Biomech*. 2006;21(5):533-537.
7. Berkowitz R, Njus G, Vrabec G. Pullout strength of self-tapping screws inserted to different depths. *J Orthop Trauma*. 2005; 19(7):462-465.

8. Andrea CR, Stover SM, Galuppo LD, Taylor KT, Rakestraw PC. Comparison of insertion time and pullout strength between self-tapping and non-self-tapping AO 4.5-mm cortical bone screws in adult equine third metacarpal bone. *Vet Surg*. 2002; 31(3):189-194.
9. Spencer JA, von Pfeil DJF, Dejardin LM, Roe SC, Weh JM. Chapter 41: internal fracture fixation. In: Johnston SA, Tobias KM, eds. *Veterinary Surgery: Small Animal*. Second ed. St. ed. Elsevier; 2018.
10. DeSoutter V-Drive User Manual: Handpiece Specifications, Buckinghamshire. UK, p. 28.
11. Kaczmarek J, Bartkowiak T, Paczos P, Zawadzki P, Łączna D, Gapiński B. What is the cost of off-Axis insertion of locking screws? A biomechanical comparison of a 3.5 mm fixed-angle and 3.5 mm variable-angle stainless steel locking plate systems. *Vet Comp Orthop Traumatol*. 2022;35(5):339-346.
12. Gallagher B, Silva MJ, Ricci WM. Effect of off-axis screw insertion, insertion torque, and plate contouring on locked screw strength. *J Orthop Trauma*. 2014;28(7):427-432.
13. Koch D. Chapter 2.1: Screws and plates. In: Johnson AL, Houlton JEF, Vannini R, eds. *AO Principles of Fracture Management in the Dog and Cat*. AO Pub. Distribution by Thieme; 2005.
14. Zahringer M, Krug B, Kamm KF, et al. Detection of porcine bone lesions and fissures: comparing digital selenium, digital luminescence, and analog film screen radiography. *AJR Am J Roentgenol*. 2001;177(6):1397-1403.


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