The Effect of Location of a Unicortical Defect on the Mechanical Properties of Rabbit Tibiae: A Model of the Distal Jig Pin Hole in Tibial Plateau Levelling Osteotomy

Max J. Lloyd[1] Daniel J. Wills[2] James D. Crowley[2] Tian Wang[2] Christopher J. Tan[2]
William R. Walsh[2]

[1] Sydney School of Veterinary Science, Faculty of Science, University of Sydney, Sydney, NSW, Australia
[2] Surgical and Orthopaedic Research Laboratories, Prince of Wales Clinical School, University of NSW, Sydney, NSW, Australia

Address for correspondence Daniel J. Wills, BVSc (Hons I), MANZCVS, Surgical and Orthopaedic Research Laboratories, Prince of Wales Clinical School, University of NSW, Sydney, NSW, 2031, Australia (e-mail: d.wills@unsw.edu.au).

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Abstract

Objective The aim of this study was to determine the effect of a unicortical defect at either the mid-diaphysis (MD) or distal metaphysis (DM) on the torsional properties of tibiae in an *in vitro* rabbit model, and to further examine optimal distal jig pin position for the canine tibial plateau levelling osteotomy (TPLO) procedure.

Study Design Thirty-eight tibiae from 19 skeletally mature female New Zealand White rabbits were assigned to one of three groups; Group 1: intact, Group 2: MD defect and Group 3: DM defect. Defects were created using a 1.6 mm Ellis pin. Pure torsion was applied to each sample and peak torque and angular displacement recorded.

Results All tibiae fractured in a spiral configuration. Fracture lines involved the defect in 33% of the MD samples and 0% of the DM samples. No differences were detected for peak torque and stiffness between groups. However, energy (mean ± standard deviation) was significantly reduced ($p = 0.028$) in the MD group (0.18 ± 0.07) relative to the intact tibia group (0.31 ± 0.14). Angle was also significantly reduced ($p = 0.040$) in the MD group (0.17 ± 0.05) compared with the intact group (0.23 ± 0.07). Placement of a DM defect had no significant effect on mechanical properties of the rabbit tibiae.

Conclusion Defects placed in the MD significantly reduced energy and angle in comparison to intact samples. No significant difference in peak torque or stiffness was observed between groups. If canine tibiae were similarly affected, our findings suggest jig pin placement in the DM to have a lesser effect on the torsional properties of the tibiae.

Keywords
- mechanical properties
- pin tract
- tibia
- tibial plateau levelling osteotomy
- stress riser

Introduction

Tibial plateau levelling osteotomy (TPLO) is a common surgical treatment for cranial cruciate ligament rupture in dogs.[1,2] Originally described by Slocum and Slocum, TPLO was performed with the use of an alignment jig,[3] which has been recommended for precise tibial plateau levelling, while maintaining tibial sagittal and torsional alignment.[4,5] Postoperative TPLO tibial fractures are a serious complication and contribute significantly to patient morbidity.[6] The

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incidence of postoperative tibial fractures is reported to range from 0.02 to 9%.[7–9] While the contribution of distal jig pin tracts to postoperative tibial fracture is unknown, Bergh and Peirone suggested that oversized or incorrectly placed jig pins may pose as a risk factor for tibial fracture.[6] Circular bone defects such as the ones produced by jig pin insertion are recognized to increase the risk of postoperative fracture due to stress concentration under torsional and bending loads.[10–12]

The TPLO jig is secured to the medial aspect of the tibia by two unicortical negative profile tip-threaded (Ellis) pins, placed proximal and distal to the osteotomy.[5] It is recommended that the proximal jig pin be placed caudal to the medial collateral ligament.[3] While commercially available jigs vary in design and consequently usable length, no specific recommendation exists for distal pin location. The objective of this study was to determine the effect of mid-diaphyseal (MD) and distal metaphyseal (DM) defects on the torsional mechanical properties of rabbit tibiae as a preclinical *in vitro* model for distal jig pin location in TPLO. We hypothesized that there would be no significant difference in the torsional mechanical properties between intact rabbit tibiae and tibiae with either a MD or DM defects.

Materials and Methods

Sample Preparation

Both tibiae were harvested from 19 skeletally mature (3.5–4.4kg) female New Zealand White rabbits that were euthanatized as part of other research projects approved by the local animal ethics committee. All soft tissue attachments were removed by sharp dissection. Tibiae were radiographed with 28kV and 45mAs in standard mediolateral and craniocaudal projections using a Faxitron X-ray machine (Faxitron X-ray Corporation, Wheeling, Illinois, United States) and digital plates (AGFA CR MD4.0 Cassette, AGFA, Mortsel, Belgium). The resulting DICOM files were reviewed using a medical image viewer (ez-DICOM medical viewer, 2002) by a trained operator to ensure the absence of any orthopaedic pathology and to confirm skeletal maturity based on closed growth plates[13] before enrolment of the sample in the study. Labelled paired samples were wrapped in 0.9% phosphate-buffered saline soaked gauze, vacuum packaged and stored at −20°C until use. Tibiae were thawed for 24 hours at room temperature prior to use.

Tibiae were randomly allocated to one of three groups; Group 1: intact ($n = 13$), Group 2: MD ($n = 13$) and Group 3: DM ($n = 12$). Tibial length was measured using digital calipers (Mitutoyo CD-6-inch CS; Absolute Digimatic, Tokyo, Japan) and was defined as the distance between the intercondylar eminence proximally and the medial malleolus distally. Craniocaudal and mediolateral diameters were measured on each sample using digital calipers at the MD and DM pin sites.

Biomechanical Testing

The proximal tibia was transected at the reproducible anatomical landmark of the tibiofibular synostosis. Mid-diaphyseal defects and DM defects were created at 50 and 6% of the original distal to proximal bone length respectively. Samples were embedded in metal pots (internal diameter 30mm) with a commercial metal alloy (Wood's metal) to a standard depth of 8 mm (►**Fig. 1A**). This depth was chosen to provide sufficient purchase of the sample while allowing exposure of the DM defect. To increase fixation of the sample within the potting medium, orthogonal Kirschner wire (1.0mm) pins were inserted through the most distal and proximal extremities of each sample (►**Fig. 1B**) using a Kirschner wire driver attachment fitted to a pneumatic orthopaedic drill (Hall Power Pro, Linvatec, Largo, Florida, United States). A potting jig and crossline laser level (CX2R Crossline laser, Lasertec, Geelong, Australia) were used to minimize variation in sample positioning/alignment in the testing apparatus.

Unicortical defects were created by a single operator (ML) in either MD or DM bone by inserting and removing a 1.6 mm Ellis pin (Veterinary Instrumentation, Sheffield, United Kingdom) using a pneumatic orthopaedic drill (Hall Power Pro, Linvatec, Largo, Florida, United States) under saline irrigation in a mediolateral fashion. Two new Ellis pins were used and alternated between samples to reduce variation in the defects attributable to cutting edge wear. Care was taken to avoid eccentric placement of the pin and the resulting defect in the bone. Mediolateral radiographs (Faxitron) were performed on all samples with defects to determine the absence of eccentrically placed drill holes and/or iatrogenic fractures resulting from drilling. Eccentrically placed drill holes were defined as those engaging the cranial or caudal cortex of the bone when viewed on the mediolateral radio-

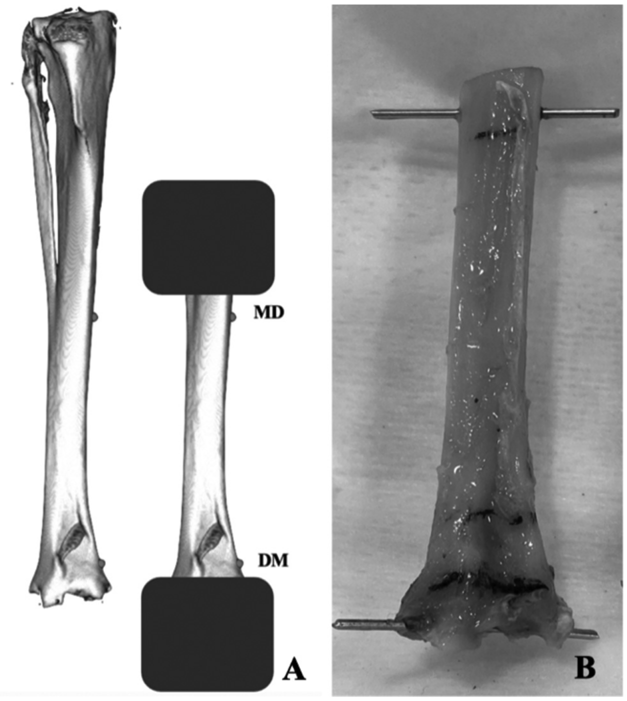

Fig. 1 The computed tomography-derived three-dimensional rabbit tibia model demonstrates the transection of the proximal tibia at the fibula synostosis and potting depth of 8mm, in relation to the mid-diaphyseal (MD) and distal metaphyseal (DM) defects (**A**). Kirschner wire (1.0mm) was inserted through the most distal and proximal extremities of each sample (**B**) to increase fixation of the sample in the Woods metal.

Fig. 2 Photograph of the mechanical testing setup with the embedded specimen attached to the load cell (bottom) and biaxial material testing machine (top).

graph. Using a previously described protocol for *in vitro* pure torsional loading of rabbit tibiae,[14] torsion under angle and load control was applied using a biaxial servohydraulic testing machine (MTS 858 Bionix testing machine, MTS systems, Eden Prairie, Minnesota, United States; ►**Fig. 2**). Controlling axial load while applying torsion eliminated compressive or tensile loading of the sample maintaining a pure torsional moment. Torsion was applied in internal rotation at a rate of 0.7 deg/s. Angular displacement (Radian) and torque (Nm) were recorded at 204.8 Hz until failure. Radiographs and photographs were taken following mechanical testing to determine fracture configuration (►**Fig. 3**).

Statistical Analysis

The size of the defect for all samples was calculated as a percentage of the craniocaudal diameter at the pin insertion site to give the defect ratio. Stiffness (Nm/Radian) was determined from the slope of the torque-angle graph. Energy absorption (Nm*Radian) was determined from the area under the curve of the torque-angle graph. Peak torque (Nm) was defined as the peak torque value recorded prior to failure. The percentage of torsional strength reduction was calculated using the peak torque (Nm) value for each group with intact bone representing 100% torsional strength.

The data were reported as mean ± standard deviation. The Shapiro–Wilk test determined that the data were normally distributed. Peak torque, stiffness, energy and angle were compared between groups (intact, MD, DM) using a one-way analysis of variance with a Games Howell Post-hoc test. Statistical analyses were performed using commercially available software (SPSS Statistics for Windows, Version 26.0. IBM Corp. Released 2018, Armonk, New York, United States). Statistical significance was established at p less than 0.05.

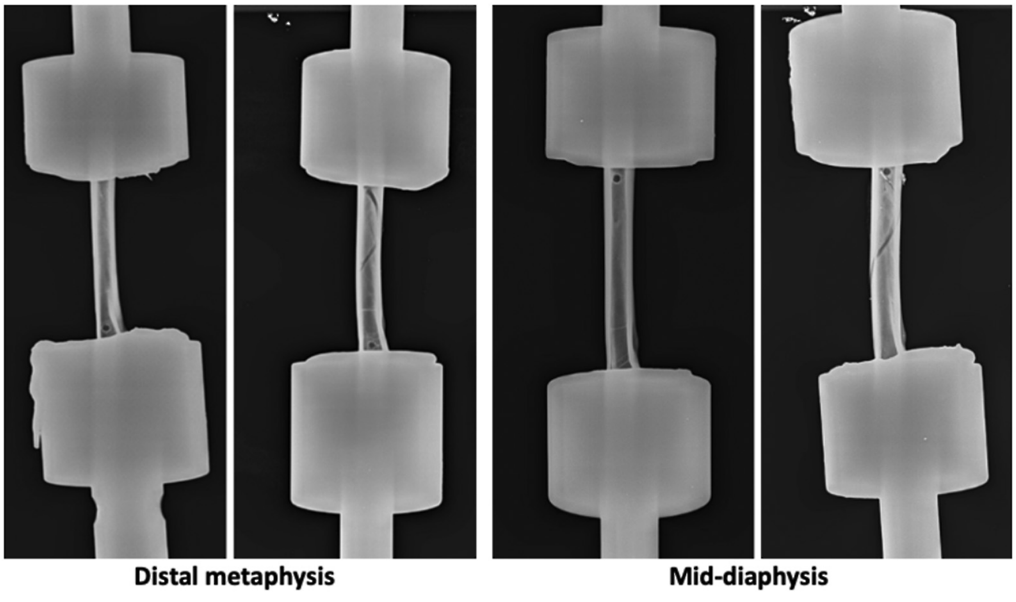

Fig. 3 Examples of pre- and post-mechanical testing mediolateral radiographs of distal metaphyseal and mid-diaphyseal samples.

Results

No problems were encountered during sample potting; all samples were stable after embedding. No fissure propagation or fractures were detected after drilling. The 1.6 mm Ellis pin created a defect approximately 25% of the craniocaudal bone diameter in both defect groups (►**Table 1**). Mid-diaphyseal spiral fracture configurations were observed in all tested samples in all three groups (►**Fig. 3**). Thirty per cent (4/13) of the MD samples had spiral fractures involving the unicortical defect. In the DM samples, none of the spiral fractures involved the defect.

Torque-angle plots demonstrated brittle material behaviour with a short nonlinear toe region, followed by a long linear elastic phase to the yield point with an absent plastic phase. This is demonstrated by ►**Fig. 4**, in which samples achieving the mean peak torque value for their respective group are plotted as a representative.

The descriptive statistics for peak torque, stiffness, energy and angle for the three groups are reported in ►**Table 2**. Mean torsional strength relative to intact tibiae decreased by 21 and 9% for tibiae with a MD and DM defect respectively.

Table 2 Descriptive statistics for peak torque, angle, energy and stiffness for intact rabbit tibiae and tibiae with MD and DM 1.6 mm unicortical defects

	Group	Mean	SD	*n*
Peak torque (Nm)	DM	2.55	0.65	12
	Intact	2.78	0.73	13
	MD	2.20	0.66	13
Angle (Radian)	DM	0.22	0.07	12
	Intact	0.23	0.07	13
	MD	0.17	0.05	13
Energy (Joules)	DM	0.27	0.11	12
	Intact	0.31	0.14	13
	MD	0.18	0.07	13
Stiffness (Nm/Radian)	DM	13.85	2.63	12
	Intact	15.62	3.84	13
	MD	15.77	3.87	13

Abbreviations: DM, distal metaphyseal; MD, mid-diaphyseal; SD, standard deviation.

Table 1 Mediolateral and craniocaudal mean (±SD) measurements of rabbit tibiae for the mid-diaphysis and distal metaphysis groups

Mid-diaphysis			Distal metaphysis		
Mediolateral diameter (mm) ± SD	Craniocaudal diameter (mm) ± SD	Defect ratio (%)	Mediolateral diameter (mm) ± SD	Craniocaudal diameter (mm) ± SD	Defect ratio (%)
7.66 ± 0.40	6.19 ± 0.43	25	10.74 ± 1.17	6.57 ± 0.67	24

Abbreviation: SD, standard deviation.
Percentage size defect created by a 1.6mm Ellis pin using the craniocaudal bone diameter is defined as the defect ratio (%).

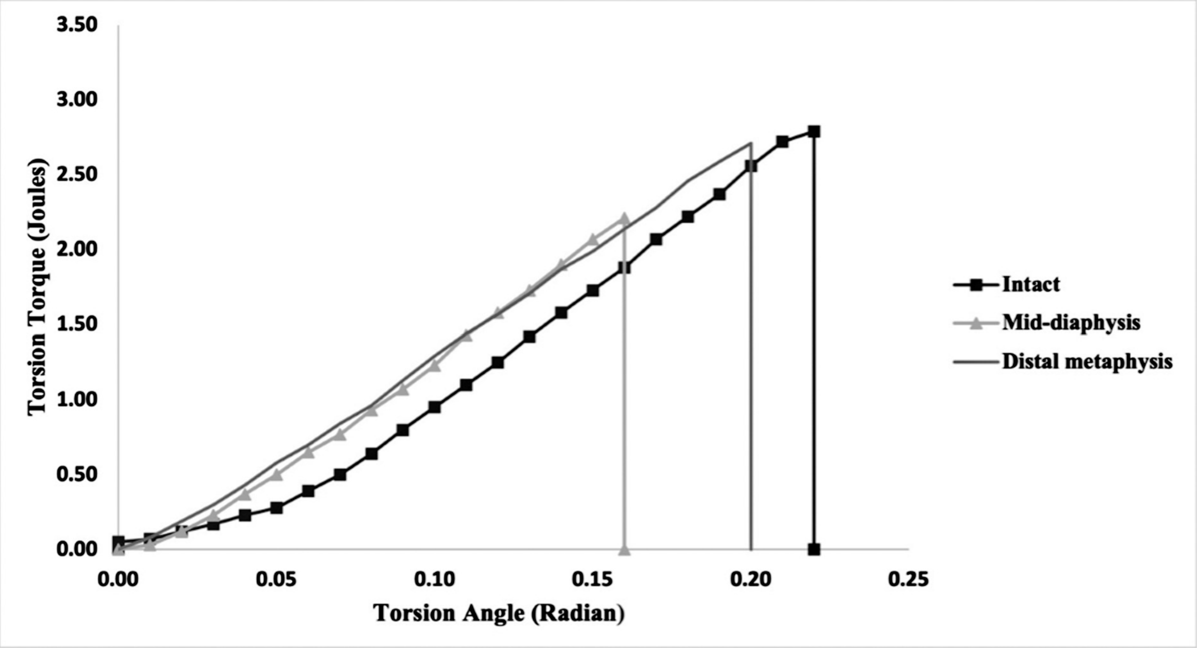

Fig. 4 Representative torque-angle plot for the intact, mid-diaphysis and distal metaphysis groups. Samples that achieved the mean peak torque value are plotted for each group.

Table 3 One-way ANOVA with Games-Howell post-hoc test for peak torque, energy, angle and stiffness for intact rabbit tibiae and MD and DM defect groups

Property			SE	*p*-Value
Peak torque (Nm)	DM	Intact	0.27691	0.692
		MD	0.26242	0.384
	Intact	DM	0.27691	0.692
		MD	0.27305	0.105
	MD	DM	0.26242	0.384
		Intact	0.27305	0.105
Angle (Radian)	DM	Intact	0.02637	0.937
		MD	0.02296	0.112
	Intact	DM	0.02637	0.937
		MD	0.02197	0.040[a]
	MD	DM	0.02296	0.112
		Intact	0.02197	0.040[a]
Energy (Joules)	DM	Intact	0.04865	0.709
		MD	0.03681	0.084
	Intact	DM	0.04865	0.709
		MD	0.04309	0.028[a]
	MD	DM	0.03681	0.084
		Intact	0.04309	0.028[a]
Stiffness (Nm/Radian)	DM	Intact	1.30754	0.384
		MD	1.31467	0.328
	Intact	DM	1.30754	0.384
		MD	1.51250	0.994
	MD	DM	1.31467	0.328
		Intact	1.51250	0.994

Abbreviations: ANOVA, analysis of variance; DM, distal metaphyseal; MD, mid-diaphyseal; SE, standard error.
[a]Significant values ($p < 0.05$).

Stiffness was decreased by 11% in tibiae with a MD defect and increased by 1% in tibiae with a DM defect. No significant differences were detected between the three groups for peak torque and stiffness (►**Table 3**). Energy was significantly reduced ($p = 0.028$) in the MD group (0.18 ± 0.07) relative to the intact tibia group (0.31 ± 0.14) (►**Table 3**). Angle was also significantly reduced ($p = 0.040$) in the MD group (0.17 ± 0.05) compared with the intact group (0.23 ± 0.07) (►**Table 3**). Hence, tibiae with an MD defect failed with a mean of 41.9% less energy and at a mean angle of displacement 26.1% smaller than that of intact tibiae.

Discussion

This study aimed to determine the effect of MD and DM defect on the torsional mechanical properties of rabbit tibiae. We hypothesized that there would be no significant difference in torsional mechanical properties between intact rabbit tibiae and tibiae with MD or DM defects. There was no significant difference between DM defects and intact tibiae. Energy and angle were significantly reduced in samples with MD defects compared with intact samples. Therefore, we rejected our null hypothesis.

Biomechanically, defects may compromise the mechanical properties of bone by acting as a stress riser.[10] In our study, placement of a defects in the MD was found to significantly reduce energy absorption and angle relative to intact samples, which are measures of toughness and ductility respectively. Reduced toughness or resistance to fracture may be attributed to stress concentration in the bone surrounding the defects. This could translate to increased risk of fracture under physiological loading, for example, fatigue failure due to progressive accumulation of energy rather than acute loading as in the current *in vitro* single load-to-failure study scenario.[15] If canine tibiae are similarly affected, these findings support the DM as the preferred site for jig pin placement during TPLO to reduce the risk of postoperative fracture.

Defects placed in the DM had no significant effect on mechanical properties compared with intact bones. This is likely a consequence of differences in cross-sectional area (►**Table 1**) and bone structure. Previous biomechanical research examining the torsional properties of intact rabbit tibiae has demonstrated torsional rigidity to be positively correlated to cortical bone area, total cross-sectional area and outer bone diameter.[16] This observed relationship is due to the cross-sectional area of bone influencing the polar moment of inertia; which is a determinant of bone's torsional strength.[17] When considering the effect of defects positioned in the broader DM compared with the narrower MD, a proportionally smaller reduction in cross-sectional area and therefore torsional strength would occur. This was demonstrated by the absence of a non-significant trend in torsional strength reduction between the DM (21%) and MD (9%) groups. Distal pin placement may therefore provide a mechanical advantage in reducing the effect of pin insertion on the torsional properties of the tibia. Disparate bone structure between the two pin sites may further influence the observed differences in mechanical properties. Specifically, the ratio of cortical to trabecular bone varies considerably between the MD and metaphysis. The metaphysis consists of a thin cortical shell overlying an internal heterogenous trabecular microstructure. The MD is composed primarily of tubular cortical bone.[18] It is these structural differences combined with differences in geometry that are likely to influence the effect of a defect on the mechanical properties of the tibia.

When selecting the appropriate TPLO jig pin size relative to the patient, limiting cortical defect size must be balanced with ensuring the rigidity of the jig. Small diameter jig pins are inherently flexible and may result in inadvertent movement of the proximal osteotomy fragment during manipulation, while larger stiffer pins increase the risk of stress riser formation. In veterinary and human orthopaedic surgery, it is recommended to limit pin diameter to one-third of the bone diameter to ensure a loss of no more than half the bone's strength.[19] This principle is derived from the landmark study by Edgerton and colleagues that investigated torsional strength reduction secondary to cortical pin tracts in sheep femora. A 1.6mm Ellis pin, resulting in approximately 25% defect, was chosen in accordance with this standard but also accommodating for the brittle nature of rabbit bone.[20,21] A reduction in tibial torsional strength of the MD group relative to intact (21%) was noted, although in the present study it did not reach statistical significance. While a larger sample size may have shown a statistical difference, a strength reduction of 21% may not be thought of as clinically significant under the current guidelines set out by Edgerton and colleagues. While these parameters will vary in the clinical scenario, it would seem prudent for the surgeon to select the smallest jig pin size without compromising stiffness of the jig pin.

Within the context of the clinical scenario, distal jig pin placement may provide further protective benefits due to differences in repair process and thinner cortices when compared with the diaphysis. The metaphyseal environment is considered to be more biologically active,[22] thus conducive to repair.[23] Unfilled drill holes in murine tibial metaphyseal bone have been demonstrated to fill with new bone 7 days earlier than a diaphyseal drill hole.[23] Heat generated from drilling is also recognized to be positively associated with cortical thickness.[24] The increased heat generated from pin placement into the cortical bone of the MD may delay new bone formation due to thermal osteonecrosis,[25] prolonging the presence of a potential stress riser in the bone. This is of particular importance when considering the propensity for Kirschner wires to produce higher temperatures in adjacent bone during insertion when compared with a standard surgical drill bit of the same size.[26]

Massie and colleagues investigated the axial compressive and torsional properties of rabbit femora with bicortical MD drill holes.[21] Bicortical 1.5 mm drill holes accounting for 25 to 32% of the bone diameter resulted in a 53% reduction in mean torsional strength.[21] In the current study, a 1.6 mm unicortical defect accounting for 25% of the MD diameter was found to reduce the tibial torsional strength by 21%. Furthermore, Massie and colleagues reported all bones with drill holes had fracture lines involving one or both bicortical defects. In contrast, our study chose a unicortical tibial defect to mimic the clinical practice of TPLO jig pin placement, resulting in only one-third of the MD group having fracture involvement of the defect. The observed differences may be due to the bone tested, the size and unicortical nature of the defect as well as the pure torsional load applied in our study. Previous studies using ovine tibiae have shown bicortical defects to reduce torsional strength by a further 26.7% when compared with that of a unicortical pin tract.[27] Increasing the size of the defect chosen may have also resulted in greater fracture involvement of the defect, given that the magnitude of strength reduction is proportional to the diameter of a circular defect.[10]

Mid-diaphyseal spiral fracture configurations were observed in all samples tested in the three groups. Fracture lines were observed to involve 30% of the MD defect, while no fracture involved the defect in the DM group. The observed MD spiral fracture pattern is consistent with torsional loading[12] and correlates with the torsional study by Paavolainen in which all rabbit tibiae fractures involved the MD.[16] Additionally, the MD region is the most commonly reported location for canine and feline tibial fractures.[28,29] In this study, spiral fractures were observed to only involve defects in the MD group. The magnitude of stress concentration in the surrounding bone produced by a defect was therefore likely greater in MD. Our results suggest distal defects may be preferred to avoid compromising the MD bone where failure occurred during torsional testing.

Eccentrically placed jig pins may result in transcortical bone defects which increase the disruption of cortical bone. Transcortical defects arising from aberrant pin placement during human orthopaedic procedures have been associated with postoperative fractures.[30,31] Given the recognized effects of cortical bone loss on torsional strength reduction,[27] care should be taken by the surgeon when using jig pins to ensure their centric positioning within the bone. In the present study, all samples were radiographed following defect creation prior to mechanical testing to ensure the absence of an eccentrically placed defect. This was conducted to eliminate the possibility of a sample with an undetected transcortical defect within the dataset.

We acknowledge some limitations of our study. Rabbit and canine tibiae have different biomechanical properties and behavior.[20,32] Rabbit tibiae were selected as a preclinical model for the dog due to greater sample accessibility. Tibiae were harvested from age and sex-matched rabbits from a closed breeding colony to minimize variation between samples. Additionally, the brittle nature of rabbit bone relative to dog bone was accounted for by the size of the defect created (~25%). Finally, our study only investigated the effect of torsional loading as this is a common physiological load applied to the tibia,[10] and one of the forces that may contribute to postoperative fracture in dogs.[12] Variation in group sample numbers may have also acted as a limitation. Future studies are required to evaluate the effect of pin tracts in compression and bending loading profiles. The effects of varying pin hole diameters, bone locations, bicortical defects and concurrent TPLO plate application are also worthy of future research.

Conclusion

Mid-diaphyseal defects significantly reduced the toughness and ductility of rabbit tibiae, while strength and stiffness remain unchanged. Distal metaphyseal defects did not influence the torsional properties of intact rabbit tibiae and were not associated with the risk of fracture resulting from the defect compared with a MD defect. The findings from this preclinical study suggest the DM jig pin site may be preferred; however, future studies with similar defects in canine tibiae are indicated.

Authors' Contributions

D.J.W. and W.R.W. conceived of the study. M.J.L., D.J.W., J.D.C., C.J.T., W.R.W. contributed to the study design. M.J.L. and T.W. acquired study data. M.J.L., D.J.W., J.D.C., C.J.T., W.R.W. contributed to drafting and revision of the manuscript, all authors read and approved the submitted manuscript and are accountable for relevant content.

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Conflict of Interest
None declared.

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