Article published online: 2023-07-20

Effect of Plate–Bone Distance and Working Length on 2.0-mm Locking Construct Stiffness and Plate Strain in a Diaphyseal Fracture Gap Model: A Biomechanical Study

Alecia Evans[1] Mark Glyde[1] Rob Day[2] Giselle Hosgood[1]

[1] School of Veterinary Medicine, Murdoch University, Perth, Australia
[2] Department of Medical Engineering and Physics, Royal Perth Hospital, Perth, Australia

Address for correspondence Alecia Evans, BSc, BVSc, GradDipEd, MVetClinStud, School of Veterinary Medicine, Murdoch University, Perth, Australia (e-mail: alecia.a.evans@gmail.com).

Vet Comp Orthop Traumatol 2024;37:1–7.

Abstract

Objective The aim of this study was to determine the effect of plate–bone distance (PBD) and working length on 2.0-mm locking compression plate (LCP) stiffness and strain in four-point bending and torsion in a diaphyseal fracture gap model.

Study Design A total of 54 LCP with three screws per fragment were assigned to one of nine combinations of working length (WL; short, medium, and long), and PBD (1, 1.5, and 3 mm) for a sample size of six per construct configuration. Stiffness was measured under quasistatic, nondestructive four-point compression bending and torsion. Plate surface strain was recorded using three-dimensional (3D) digital image correlation during four-point compression bending.

Results WL had a significant effect on overall construct stiffness in both compression bending and in torsion, with shorter WL constructs having higher stiffness ($p < 0.0001$). PBD had no effect on construct stiffness in compression bending; however, a significant reduction in stiffness was noted in torsion ($p = 0.047$) as PBD incrementally increased. WL had a significant effect on plate strain in compression bending, with shorter WL constructs having lower plate strain ($p < 0.0001$). PBD had no effect on plate strain in compression bending except for lower plate strain recorded in long WL constructs with 1-mm PBD, compared with 1.5- and 3-mm PBD constructs ($p < 0.0001$).

Conclusion Longer WL constructs, regardless of PBD, had lower stiffness in compression bending, while in torsion, some modulation of this effect was noted with incremental decreases in PBD. Longer WL resulted in high plate strain, regardless of PBD.

Keywords
- biomechanics
- working length
- plate–bone distance
- stiffness
- strain

Introduction

Adequate understanding of the biomechanical requirements for repair of a particular fracture is necessary to ensure that the chosen repair will remain biomechanically effective for the time required for fracture healing. Construct stiffness has been shown to be a determinant of the type and rate of fracture healing, with inadequate stiffness contributing to delayed healing or nonunion,[1] or implant-fatigue failure.[1–4] Implants with lower stiffness will undergo higher stress,

received
March 16, 2023
accepted after revision
June 9, 2023
article published online
July 20, 2023

Georg Thieme Verlag KG,
Rüdigerstraße 14,
70469 Stuttgart, Germany

DOI https://doi.org/10.1055/s-0043-1771198.
ISSN 0932-0814.

which has been shown to increase the risk of fatigue failure.[5,6]

Plate working length significantly affects the stiffness of a construct; however, conflicting interpretations of investigations are cited.[1–4,7] Stoffel and colleagues[4] reported that a longer plate working length resulted in less construct stiffness in a 4.5-mm locking compression plate (LCP) fracture gap model with a 6-mm fracture gap. However, in a 1-mm gap model, longer working lengths had higher construct stiffness due to deformation of the construct resulting in transcortical contact and load sharing. Whether the *in vivo* increase in stiffness in the 1-mm gap model would be sustainable in a clinical case due to the resultant high interfragmentary strain produced on transcortical contact is questionable. Similar discrepancies have been cited regarding the effects of working length on plate strain; however, recent biomechanical studies[2,3,8] showed that a short working length had lower plate strain than a long working length.

Plate–bone distance, or *standoff*, can also affect construct stiffness. Ahmad and colleagues[9] reported plastic deformation and failure at lower loads in 4.5-mm LCP constructs with a 5-mm plate–bone distance compared with a 2-mm plate–bone distance. Other studies in human orthopaedics have shown that greater plate–bone distance results in less construct stiffness in both axial compression and torsion.[4,10] No published studies have evaluated the effect of plate–bone distance in small locking constructs such as those used in small animal orthopaedics. Furthermore, no studies have examined the interaction between working length and plate–bone distance in locking constructs, nor plate strain associated with varying plate–bone distance.

The objectives of this study were to determine the effect of three working lengths in combination with three plate–bone distances on 2.0-mm locking construct stiffness and strain in a diaphyseal fracture gap model. It was hypothesized that a long working length or greater plate–bone distance would result in low construct stiffness in compression bending and torsion, and high plate strain in compression bending. We also hypothesized that there would be an interaction between plate–bone distance and working length for both stiffness and strain.

Materials and Methods

A mid-diaphyseal fracture gap model was created with polyacetal tubing (Delrin, McMaster-Carr, Elmhurst, IL, United States) with an outer diameter of 12.7 mm and an inner diameter of 6.35 mm. Each Delrin fragment was drilled with a computer-controlled mill using a 1.5-mm drill bit as per AO guidelines for 2.0-mm locking screws.[11] Each fragment had all five potential screw holes drilled at a distance of 7 mm between the center of adjacent holes, with the center of the innermost screw hole positioned 2.5 mm from the fragment-fracture end. Each tube was also predrilled with a 4.0-mm screw hole, 35 mm from the distal end of the tube. This hole was used for screw fixation to the loading jig to prevent relative motion during testing. The Delrin tubes were stabilized with a 12-hole 2.0-mm LCP (DePuy Synthes, Paolo, PA, United States), with three bicortical locking screws in each fragment in a symmetrical configuration with a 6-mm fracture gap centered over the sixth combination screw hole (►**Fig. 1**). To enable a change in plate working length with no change in screw number and symmetrical screw placement on either side of the fracture gap with a single central vacant hole spanning the fracture gap, a 12-hole 2-mm LCP was used leaving a single unused plate hole at one end of the plate.

Construct Configuration

Three different working lengths were generated by applying three different screw configurations. The screw configurations were symmetrical in each fragment. The screw holes were numbered, with "1" being the screw hole adjacent to the slipper toe end of the plate and "11" being the screw hole adjacent to the stacked hole. The stacked hole was not filled in any construct and the fracture gap spanned the sixth hole in all constructs. All screws were 2.0-mm locking screws (20-mm length, self-tapping locking screws, DePuy Synthes)

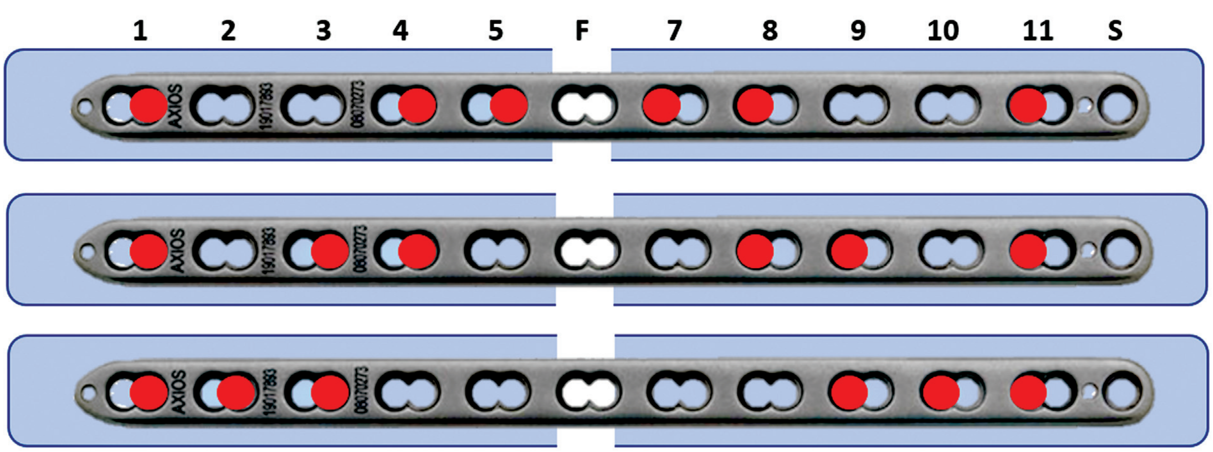

Fig. 1 Schematic showing working length configurations. A 12-hole 2.0-mm LCP with locking holes numbered from 1 through 11, with "F" indicating the fracture gap spanning hole 6 and "S" the stacked hole, which was not used in any of the tested constructs.

inserted bicortically with a standardized insertion torque of 0.4 Nm (Torque limiter, 0.4 nM with AO quick coupling, DePuy Synthes), as per AO recommendations for 2.0-mm locking screws.[11] The short working length constructs had screws in plate holes 1, 4, 5 and 7, 8, 11; the medium working length constructs had screws in plate holes 1, 3, 4, and 8, 9, 11; and the long working length constructs had screws in plate holes 1, 2, 3, and 9, 10, 11 (►**Fig. 1**).

Plate–bone distance was maintained with rigid plastic spacers (tiling spacers, Rubi, Spain, and Qep Australia) during screw insertion, with 1-, 1.5-, and 3-mm spacers. Prior to construct assembly, a sample of 20 spacers from each size were selected and measured with vernier callipers, confirming their reported thickness (1-mm spacers: mean 1.00 mm [SD ± 0 mm]; 1.5-mm spacers: mean 1.48 mm [SD ± 0.06 mm]; 3-mm spacers: mean 2.94 mm [SD ± 0.07 mm]). Each construct was assembled by a European College of Veterinary Surgeons board-certified surgeon (MG).

A sample size of six replicates per construct configuration was used, for a total of 54 constructs. A sample size of six would detect a minimum effect size of 1.75 (power = 0.8; $\alpha = 0.05$; error variance = 10%), which was sufficient based on previously reported data.[8]

Biomechanical Testing

Nondestructive Four-Point Bending

The assembled constructs were fixed in a custom loading jig with a 4.0-mm screw in the predrilled jig-positioning hole to prevent rotation during testing. Each end of the fully assembled construct was seated 35 mm within the custom loading jig (►**Fig. 2**). Each construct underwent a four-point compression bending by a materials testing machine (Instron 5566, Instron, Norwood, MA, United States) with a 100-N load cell applied parallel to the screw axis and the plate positioned on the compression surface. A support roller with 290-mm spacing supported the constructs within the loading jig, and a load roller with 230-mm spacing allowed a uniform load and bending moment to be applied to the construct. Each construct was preloaded to 0.4 N, then ramp loaded for three cycles under displacement control at 10 mm/min to a force of 40 N, as per a previously published protocol.[2] This load protocol produced a peak bending moment of 0.6 Nm in compression bending which is within the elastic limits of the constructs based on previous testing. Eighteen complete sets of implants were used in this study and reconfigured twice to allow evaluation of 54 different constructs (6 replicates of 9 different configurations). Randomization of construct testing order was determined by assigning each construct replicate a number between 1 and 54 and determining the order of testing using a random number generator.

Nondestructive Torsion

The constructs were secured in a custom jig, clamped at one end, while the opposite end of the construct was supported while still allowing free rotation around the construct's longitudinal axis. The constructs were placed in the jig horizontally and load was applied to the distal jig screw resulting in a lever arm of 25 mm. Torque was applied to the construct with each construct loaded to 0.4 N before undergoing three consecutive cycles of load under displacement control at 10 mm/min, resulting in a torsional displacement of approximately 11 degrees. All constructs were loaded to a minimum peak load of 20 N.

Stiffness and Strain

All data from the material testing were measured at a rate of 10 Hz. All constructs underwent three loading cycles in each direction of testing (compression bending and torsion). As per previously published protocols,[2,3,8] the load displacement measurements were recorded from the third cycle of

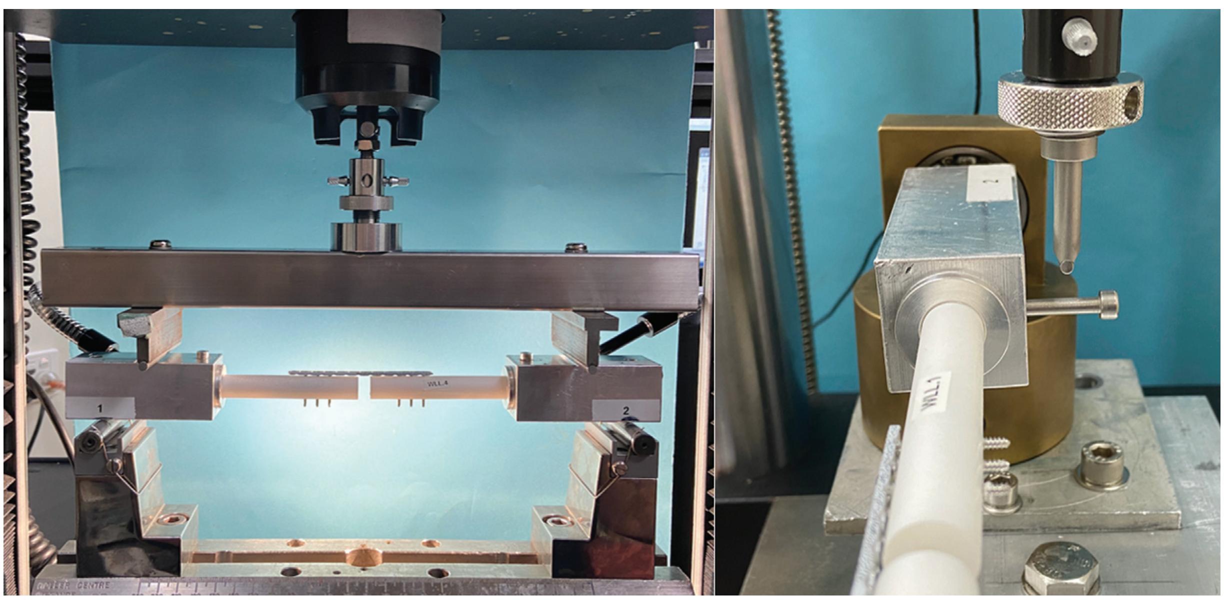

Fig. 2 Biomechanical testing setup for four-point compression bending (left) and torsion (right).

Table 1 Mean stiffness (N/mm) across working lengths and plate–bone distance in compression bending

	Short working length	Medium working length	Long working length
Plate–bone distance of 1 mm	33.751[a] (95% CI: 31.48–36.02)	25.170[b] (95% CI: 23.66–26.68)	19.651[c] (95% CI: 18.7–20.61)
Plate–bone distance of 1.5 mm	36.323[a] (95% CI: 33.27–39.38)	24.793[b] (95% CI: 23.6–25.98)	18.626[c] (95% CI: 17.8–19.45)
Plate–bone distance of 3 mm	33.726[a] (95% CI: 31.19–36.27)	25.532[b] (95% CI: 24.33–26.74)	18.209[c] (95% CI: 17.34–19.08)

Abbreviation: CI, confidence interval.
Note: Means with the same superscript are not significantly different ($p \leq 0.05$).

testing. The bending and torsional stiffness for each construct was determined from the slope of the linear elastic portion of the load displacement curve.

Strain data were collected with three-dimensional digital image correlation (DIC), which allowed precise measurement of plate strain within a specified field of view.[2,12] Plate strain was measured during compression bending only. A speckle pattern on the surface of the plates enabled correlation-based displacement measurements to calculate strain.

The speckle pattern for strain analysis was applied using a hand speckled technique. All plates were sprayed with a base coat of matt white spray paint and allowed to dry before being speckled with a 0.05-mm black pigment marker. As per recommendations for DIC analysis, the speckles were placed in a random distribution, with a density of approximately 50%.[13] All speckles were applied by the same investigator (AAE) using magnifying loupes.

High-definition recordings were collected with stereoscopic video cameras, with image capture performed using VIC-Snap software (VIC-Snap software, Correlated Solutions Inc., Irmo, SC, United States). Given the symmetrical configuration of the constructs, the field of view for image correlation was focused on the plate spanning holes 1 to 6 including the fracture gap. The region of interest for strain evaluation was defined as the region of the plate over the fracture gap. The von Mises strain for each construct was plotted against load (N), and a line of best fit was used to calculate the strain at a load of 40 N.

Statistical Analysis

Data were evaluated for normality with a Shapiro–Wilk test and non-normal data transformed. Data were summarized as mean, SD, and 95% confidence interval of the mean. Stiffness and strain data were analyzed using a two-way ANOVA, including the fixed effects of working length and plate–bone distance, and the interaction. *Post hoc* pairwise comparisons were made when there were significant model effects, tested against a Tukey adjusted $p \leq 0.05$.

Results

Stiffness

In four-point compression bending, there was a significant interaction between working length and plate–bone distance ($p = 0.04$). All short working length constructs, regardless of plate–bone distance, were stiffer than all medium working length constructs, which in turn were stiffer than all long working length constructs. The plate–bone distance did not affect construct stiffness in bending within any working length (►**Table 1**).

In torsion, there was no significant interaction between working length and plate–bone distance ($p = 0.216$) but significant main effects of working length ($p < 0.0001$) and plate–bone distance ($p < 0.0001$; ►**Table 2**). All short working length constructs, regardless of plate–bone distance, were stiffer than all medium working length constructs, which in turn were stiffer than all long working length construct, except for the medium working length with the 3-mm plate–bone distance, which was not different from the long working length with the 1 mm plate–bone distance. The effect of plate–bone distance was evident within the short and long working lengths, with stiffness significantly lower for the 3-mm plate–bone distance than the 1.5- and 1.0-mm plate–bone distance ($p < 0.0001$ and 0.047 for short and long working length, respectively). There was no discernible effect of plate–bone distance on stiffness for the medium working length. A *post hoc* sample size calculation for the medium working length group determined a sample

Table 2 Mean stiffness (N/degree) across working lengths and plate–bone distance in torsion

	Short working length	Medium working length	Long working length
Plate–bone distance of 1 mm	1.487[a] (95% CI: 1.41–1.566)	1.15[c] (95% CI: 1.072–1.228)	0.966[de] (95% CI: 0.881–1.053)
Plate–bone distance of 1.5 mm	1.445[a] (95% CI: 1.39–1.492)	1.128[c] (95% CI: 1.067–1.189)	0.913[ef] (95% C.I 0.845–0.979)
Plate–bone distance of 3 mm	1.287[b] (95% CI: 1.214–1.361)	1.062[cd] (95% CI: 1.028–1.096)	0.844[f] (95% CI: 0.774–0.914)

Abbreviation: CI, confidence interval.
Note: Means with the same superscript are not significantly different ($p \leq 0.05$).

Table 3 Mean surface strain on the plate at the level of the fracture gap (mm/mm, reported $\times 10^{-5}$) across working lengths and plate–bone distance in compression bending

	Short working length	Medium working length	Long working length
Plate–bone distance of 1 mm	358^{ad} (95% CI: 324–392)	636^{bcd} (95% CI: 582–690)	476^{e} (95% CI: 387–565)
Plate–bone distance of 1.5 mm	344^{ad} (95% CI: 297–390)	648^{bcd} (95% CI: 579–716)	711^{b} (95% CI: 628–794)
Plate–bone distance of 3 mm	354^{ad} (95% CI: 279–429)	608^{c} (95% CI: 518–697)	698^{b} (95% CI: 627–768)

Abbreviation: CI, confidence interval.
Note: Means with the same superscript are not significantly different ($p \leq 0.05$).

size of nine replicates would be required to detect significance, suggestive of type II error.

Strain

There was a significant interaction effect for working length and plate–bone distance ($p < 0.0001$) on plate strain in compression bending (►**Table 3**). Within the short and medium working lengths, there was no significant difference in plate strain over the fracture gap for different plate–bone distances ($p = 0.71$–0.91 and 0.30–0.75, respectively). Within the long working length group, there was significantly lower plate strain for the 1-mm plate–bone distance than both the 1.5-mm ($p < 0.0001$) and 3-mm ($p < 0.0001$) plate–bone distances, which were not different from each other ($p = 0.73$).

Across working length groups, the plate strain was significantly lower for the short working length when compared with the medium working length ($p < 0.0001$) and the long working length ($p < 0.0001$–0.0038) constructs, regardless of the plate–bone distance.

Discussion

Based on the findings of our study, we accepted our hypothesis that a long working length would result in low construct stiffness in compression bending and torsion, and high plate strain in compression bending. We partially rejected our second hypothesis, however, with a greater plate–bone distance resulting in lower construct stiffness in torsion only, but a higher plate strain was observed for greater plate–bone distance under compression bending. The results of our study support the previously published literature on plate working length, showing that a long working length has lower construct stiffness in a fracture gap model compared with a short working length under both bending and torsional loads.[2–4,12] Furthermore, our study has demonstrated that plate strain over the fracture gap was significantly lower in constructs with a short working length. This finding is consistent with previous published studies.[2–4,12,14]

Working length was the major determinant of construct stiffness and strain, with plate–bone distance only having a detectable effect in torsional loading, where overall stiffness of the constructs was much less than in bending loads. With each incremental increase in working length, construct stiffness was lower in both bending and torsion, and plate strain was higher in bending. Historic controversy around the effect of working length stems from the results of a 1-mm fracture gap model in a finite element analysis study,[4] where transcortical contact during construct loading produced load sharing. In this 1-mm fracture gap model, a longer working length paradoxically resulted in high stiffness subsequent to transcortical contact and consequently lower plate strain. Somewhat surprisingly, this led to the recommendation to increase working length in narrow fracture gap scenarios to facilitate early transcortical contact. In an *in vivo* situation, however, repetitive transcortical contact would, in the absence of plastic deformation of the plate, result in unsustainably high interfragmentary strain of 100%. This would necessitate bone resorption and widening of the fracture gap to attempt to reduce interfragmentary strain to a level compatible with the production of fibrous tissue.[6,15,16] Whether fatigue implant failure would then occur in this situation *in vivo* would depend on the biologic capacity of the fracture site, the fatigue life of the implant, and the frequency and magnitude of cyclic loading. Given the results of our study, and other recently published evidence, it is reasonable to conclude that a construct with a longer working length would be at greater risk of implant failure than a construct with a shorter working length.[2–4,12,14]

Our study shows no effect of increasing plate–bone distance in bending. Under torsional loading, however, incremental increases in plate–bone distance in short and long working length constructs resulted in significantly lower stiffness. For medium working length constructs, however, increments in plate–bone distance did not significantly affect stiffness. We consider the absence of difference for medium working length constructs is most likely the result of type II error.

In our model, any effect of increasing plate–bone distance was not detected in four-point compression bending. This differs from previous studies[4,9] where a significant reduction in stiffness in axial compression was noted when plate–bone distance was greater than 2 mm. Both of the cited studies utilized axial compression for bending, which creates a tensile load on the plate, which differs from the compression bending induced in our study. Many previous biomechanical studies evaluate tension bending and/or axial compression, as these are considered to mimic physiologic forces on a fracture repair due to the eccentric position of bone plates relative to the mechanical axis of long bones.[4,6,7,9,10,17,18]

Loading of fracture gap models in this mode causes the fracture gap to close at the trans-cortex. In constructs with low stiffness, this can result in contact between the bone model fragments, causing load sharing between the bone column and implants.[4,19] Furthermore, tension bending can also result in plate–bone contact at the level of the fracture gap, which reduces the working length defined by screw position to a working length equivalent to the fracture gap.[19,20] Given that our study aimed to evaluate a true load-bearing construct with working length as a primary explanatory variable, we elected to test compression bending to prevent any bone–bone or bone–plate contact during testing, which could confound results.

Both compression and tension bending induce both bending and shear loads on the exposed shaft of the screw, with a greater plate–bone distance increasing the length of screw shaft exposed to these loads. Axial compression results in a nonuniform bending moment, with greater bending moments experienced at the center of the construct. This increases the shear and bending loads on the screws, which will magnify the effect of increasing plate–bone distance in axial compression. In the locking plate study by Ahmad and colleagues,[9] implant failure through screw head loosening was identified in three samples, which for locking constructs is critical for maintaining the strength of the implant. As a result, this may have resulted in the reduction in construct stiffness noted with increasing plate–bone distance in axial compression in that study.

A previous study[10] evaluated both bending and axial compression using dynamic compression plates, and identified a greater magnitude of stiffness reduction with increasing plate–bone distance in axial compression compared with four-point bending. Since dynamic compression plates were used, these findings cannot be directly applied to the model used in the present study; however, they highlight the importance of experimental design and load conditions on construct stiffness. Axial compression and four-point compression bending differ in the bending moment produced, with a uniform bending moment in four-point compression bending compared with three-point tension bending produced through axial compression. The nonuniformity of the bending moment, and the subsequent increase in bending and shear loads experienced by the screws may explain why construct stiffness has differed for the same constructs under axial compression versus four-point bending in previous studies.

While no effect of plate–bone distance on stiffness was detected in compression bending, a significant effect on stiffness was noted in torsion, with a plate–bone distance of 3 mm resulting in significantly reduced torsional stiffness. Reduced torsional stiffness with greater plate–bone distance has previously been demonstrated in larger locking plates (4.5- and 5.0-mm LCP), with plate–bone distances greater than 2 mm shown to have significantly decreased torsional stiffness and lower overall loads to failure.[4,9,17] The decreased torsional stiffness of implants with a greater plate–bone distance can be attributed to the increasing length of exposed screw shaft being less resistant to torsional forces compared with axial forces.[9,10]

Our results demonstrated a significant interaction between working length and plate–bone distance, with a compounded reduction in stiffness noted for the longest working length and the greatest plate–bone distance. The same construct configuration was also identified to have the highest plate strain in compression bending. This interaction was more evident under torsion testing, where the effect of a long working length could be modulated by a low plate–bone distance. While not evaluated in the current study, we would hypothesize that minimizing the plate–bone distance in a long working construct would also reduce plate strain in torsion. While this is a biomechanical model rather than a clinical study, these results suggest that when the fracture configuration forces the use of a longer working length, efforts should be made to minimize the plate–bone distance to optimize construct stiffness. Knowledge of the interaction between a long working length and a higher plate–bone distance may necessitate consideration of augmenting the repair to ensure adequate stiffness.

In our model, working length was the overwhelming determinant of construct stiffness and plate strain, with plate–bone distance only a significant factor in torsional loading. A long working length results in lower construct stiffness in compression bending and in torsion, and results in higher plate strain in compression bending. A significant interaction between working length and plate–bone distance in torsion shows that using a small plate–bone distance could modulate the loss of stiffness and increase in strain produced by a long working length.

Authors' Contribution

A.E. and M.G. contributed to conception of the study, study design, acquisition of data, data analysis and interpretation, and manuscript preparation and review. R.D. contributed to study design, acquisition of data, data analysis and interpretation, and manuscript preparation and review. G.H. contributed to conception of study, study design, acquisition of data, data analysis and interpretation, manuscript preparation and review. All the authors revised and approved the submitted manuscript.

Funding

Implants used in this study were funded by a materials grant from Zebravet Australia.

Conflict of Interest

None declared.

References

1 MacLeod AR, Pankaj P. Pre-operative planning for fracture fixation using locking plates: device configuration and other considerations. Injury 2018;49(Suppl 1):S12–S18

2 Bird G, Glyde M, Hosgood G, Hayes A, Day R. Effect of plate type and working length on a synthetic compressed juxta-articular fracture model. VCOT Open 2020;03(02):e119–e128

3 Bird G, Glyde M, Hosgood G, Hayes A, Day R. Biomechanical comparison of a notched head locking T-plate and a straight locking compression plate in a juxta-articular fracture model. Vet Comp Orthop Traumatol 2021;34(03):161–170
4 Stoffel K, Dieter U, Stachowiak G, Gächter A, Kuster MS. Biomechanical testing of the LCP: how can stability in locked internal fixators be controlled? Injury 2003;34(Suppl 2):B11–B19
5 Sistaninia M, Niffenegger M. Fatigue crack initiation and crystallographic growth in 316L stainless steel. Int J Fatigue 2015; 70:163–170
6 Roe S. Biomechanics of fracture fixation. Vet Clin North Am Small Anim Pract 2020;50(01):1–15
7 Maxwell M, Horstman CL, Crawford RL, Vaughn T, Elder S, McLaughlin R. The effects of screw placement on plate strain in 3.5 mm dynamic compression plates and limited-contact dynamic compression plates. Vet Comp Orthop Traumatol 2009;22(02): 125–131
8 Pearson T, Glyde M, Hosgood G, Day R. The effect of intramedullary pin size and monocortical screw configuration on locking compression plate-rod constructs in an in vitro fracture gap model. Vet Comp Orthop Traumatol 2015;28(02):95–103
9 Ahmad M, Nanda R, Bajwa AS, Candal-Couto J, Green S, Hui AC. Biomechanical testing of the locking compression plate: when does the distance between bone and implant significantly reduce construct stability? Injury 2007;38(03):358–364
10 Kowalski MJ, Schemitsch EH, Harrington RM, Chapman JR, Swiontkowski MF. A comparative biomechanical evaluation of a noncontacting plate and currently used devices for tibial fixation. J Trauma 1996;40(01):5–9
11 Johnson AL, Houlton JEF, Vannini R. AO Principles of Fracture Management in the Dog and Cat. Davos Platz, Switzerland: AO Pub.; Distribution by Thieme; 2005
12 Pearson T, Glyde MR, Day RE, Hosgood GL. The effect of intramedullary pin size and plate working length on plate strain in locking compression plate-rod constructs under axial load. Vet Comp Orthop Traumatol 2016;29(06):451–458
13 Correlated Solutions Speckle Pattern Fundamentals. Accessed Juned 25, 2023 at: https://correlated.kayako.com/article/38-speckle-pattern-fundamentals
14 Märdian S, Schaser KD, Duda GN, Heyland M. Working length of locking plates determines interfragmentary movement in distal femur fractures under physiological loading. Clin Biomech (Bristol, Avon) 2015;30(04):391–396
15 Miramini S, Zhang L, Richardson M, et al. Computational simulation of the early stage of bone healing under different configurations of locking compression plates. Comput Methods Biomech Biomed Engin 2015;18(08):900–913
16 Perren SM. Physical and biological aspects of fracture healing with special reference to internal fixation. Clin Orthop Relat Res 1979;(138):175–196
17 Liu W, Yang L, Kong X, et al. Stiffness of the locking compression plate as an external fixator for treating distal tibial fractures: a biomechanics study. BMC Musculoskelet Disord 2017;18(01):26
18 Ghimire S, Miramini S, Richardson M, Mendis P, Zhang L. Effects of dynamic loading on fracture healing under different locking compression plate configurations: a finite element study. J Mech Behav Biomed Mater 2019;94:74–85
19 Hoffmeier KL, Hofmann GO, Mückley T. Choosing a proper working length can improve the lifespan of locked plates. A biomechanical study. Clin Biomech (Bristol, Avon) 2011;26(04):405–409
20 Chao P, Conrad BP, Lewis DD, Horodyski M, Pozzi A. Effect of plate working length on plate stiffness and cyclic fatigue life in a cadaveric femoral fracture gap model stabilized with a 12-hole 2.4 mm locking compression plate. BMC Vet Res 2013;9(01):125

