The strain paradox: dispelling myths about plate working length and understanding how the decisions you make affect the life of your implants

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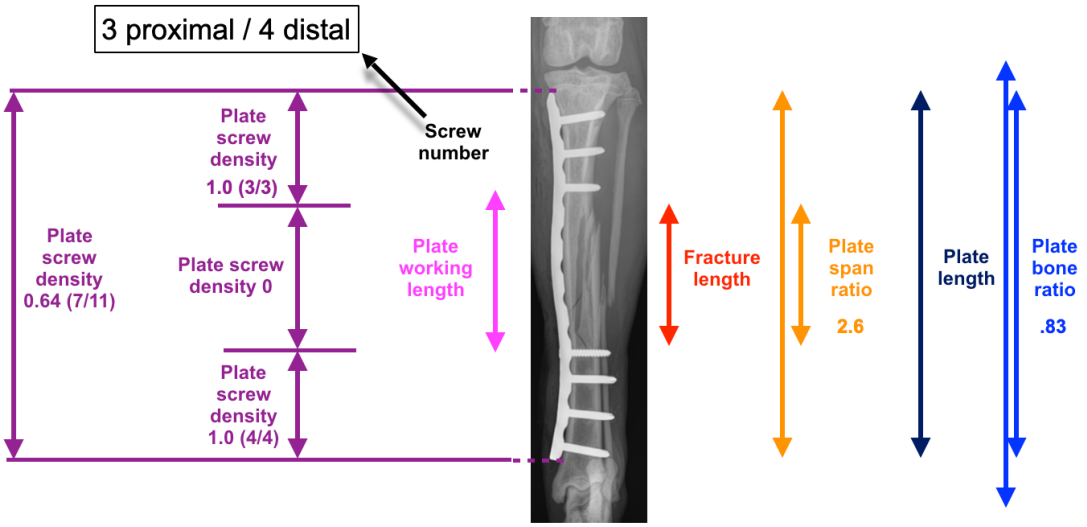
The aim of this section is to review the potential biomechanical effects of decisions on plate and screw placement in treating simple and comminuted diaphyseal fractures to inform your pre-operative decision-making.

Considerable information exists in the human orthopaedic literature that informs decision-making in plate application in animals. Several factors influence the stability of a diaphyseal fracture repaired with a bone plate. These include the fracture type (simple compressed, simple uncompressed, comminuted), plate size and length, the plate type (locked or non-contact vs unlocked or contact plates), plate stand-off distance, screw type, number of screws per fragment and position of screws within the fragment.

Some important definitions:

- 2 basic principles of internal fixation
    - interfragmentary compression – rigid fixation for simple (non-comminuted) fractures. Intention is to achieve load-sharing and absolute stability.
    - splinting – more flexible fixation for comminuted fractures. Intention is to achieve bridging fixation and relative stability.



- Plate bone ratio
    - ratio of plate length relative to bone length

- Plate span ratio
    - ratio of fracture gap length to plate length

- Plate screw density
    - ratio of number of screws to the number of holes in the plate or number of holes in the plate for a bone segment

- Plate working length
    - distance between the screws closest to the fracture gap (for non-contact or locked plates with no bone contact at main fragment ends)
    - distance between the main fragment ends for contact or non-locked plates if loading occurs in such a way to create tension bending (for example axial compression of a laterally plated femur fracture). For compression bending or for torsional loads, the plate working length is the distance between the screws closest to the fracture gap.

- Plate stand-off distance is the distance between the plate and the bone

- Stiffness
    - The ability of a construct (implant and fractured bone combined) to resist deformation under an applied load (N/mm). Stiffness is measured from the slope of the Load vs Deformation curve in the linear elastic region (see image below).

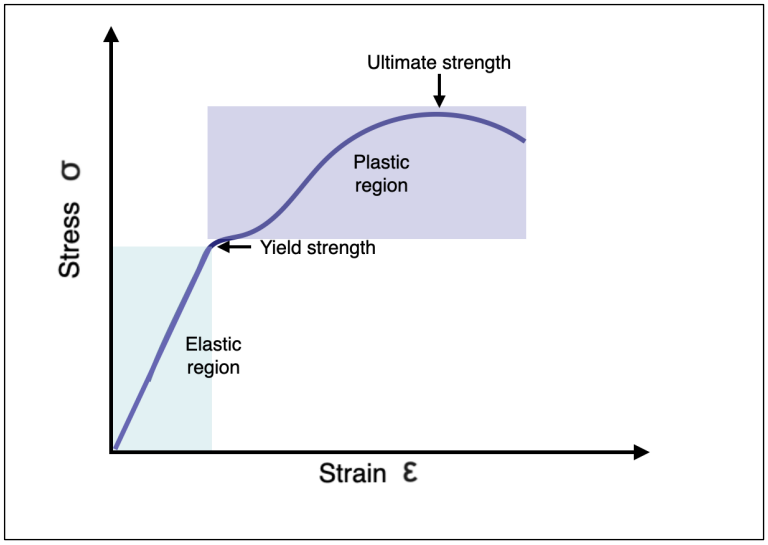
- Strength
    - The maximum load an implant or construct can withstand before failure.

- Strain
    - Also known as unit deformation. Normal or axial strain is defined as the ratio of the change in length to the original gage length

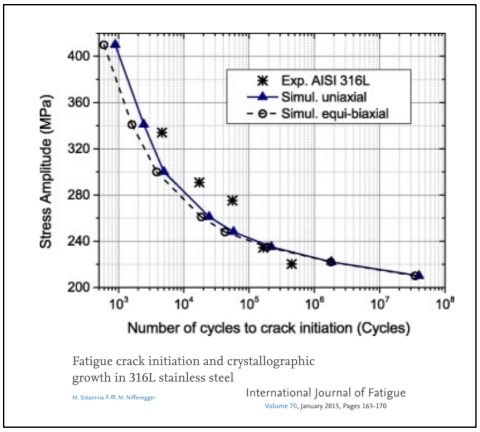
$$\varepsilon = \Delta L / L$$

    - In plate fixation of fractures, plate strain is the deformation of the implant, while interfragmentary strain is the deformation of the fracture gap(s). These must be considered separately.
    - Plate or implant surface strain can be measured using strain gauges or, more commonly these days, using optical strain measurements

- Stress
  - The resistance of a material to forces applied to it, defined as the amount of load per cross-sectional area (N/mm^2). Implant stress is calculated.
  - As can be seen from the Stress vs Strain curve image below, there is a linear relationship between stress and strain within the linear elastic region of the curve, prior to plastic deformation. For this reason, surface strain is used as a measurable surrogate for stress.



- Fatigue failure
  - the most common cause of implant failure, results from cumulative or repetitive stress that exceeds the fatigue life of the implant.
  - Implants experiencing higher stress (strain) will fatigue or fail after fewer cycles (steps) compared to implants experiencing lower stress. This is depicted in a Stress vs Cycles (S vs N) curve.



What plate size is appropriate?

Validated guidelines on appropriate plate size in animals do not exist. This is understandable given the almost 100-fold range in small animal patient weight and the great variation in activity levels during the healing period.

Plate-weight charts exist and are useful though usually gives several size options, which reflects the importance of fracture assessment in every case. Anatomically reconstructed fractures that are compressed and single limb would have a good biomechanical assessment as they are load-sharing constructs and generally would not require a “large size” implant. Non-compressible short oblique fractures and comminuted fractures require bridging fixation with the implants being load-bearing. These would require a larger sized fixation option and/or augmentation with some method (for example plate-rod fixation, orthogonal plate fixation, dual bone fixation, double plate fixation) to prevent acute failure, where the implant is not sufficiently strong, and to prevent fatigue failure where the number of cycles (steps) exceeds the fatigue life of the implant.

Guidelines of plate width not exceeding bone width and maximum screw diameter of less than or equal to 30% of the bone diameter are also useful subjective guidelines. In the majority of cases screw-bone ratio is 20-30%.

Biological assessment as part of fracture assessment should provide a good indication of likely healing time. Prolonged healing times can be expected to place increased cyclic loading on plates and, where stable load-sharing is not achieved, larger plate size or strategies to prevent cyclic failure such as plate-rod constructs, orthogonal plates, dual bone fixation etc should be considered.

Similarly, where unrestricted periods of exercise in the healing period are expected, similar strategies to prevent acute overload failure and fatigue or cyclic failure should be considered.

Stress protection, where the implant is relatively “oversized” for the bone, is certainly seen in small animals. Toy breed radius and ulna fractures would be the main common example of this. This is a product of Wolff’s Law, where the implant size is such that it prevents the radius and ulna taking sufficient weight-bearing loads leading to some degree of bone loss. Implant failure through relative “undersizing” of the implant, is a much more common *clinically significant* complication of fracture repair. This reflects the challenges we face in small animal surgery compared to human surgery where postoperative activity levels in our patients are understandably very commonly poorly controlled. This creates the situation where we need to create constructs that are strong enough and stiff enough to withstand the biomechanical demands before bone union, but that are not “inappropriately” stiff to prevent load transfer into the bone.

What plate length is appropriate?

Screw distribution within the plate obviously depends on plate length. Gautier and Sommer (2003) wrote a landmark paper on Guidelines for the clinical application of the LCP. In this paper they recommended the ideal plate length can be determined by consideration of 2 values – the plate span ratio and the plate screw density. This recommendation was largely based on a retrospective case series of 81 human femoral shaft fracture treated with contact plating of various types by Rozbruch and Gautier et al (1998).
In this case series they found the best predictor of successful fracture healing using logistic regression analysis was an increase plate length.

Gautier and Sommer empirically recommended the plate span ratio should be > 8-10 in simple fractures and >2-3 in comminuted fractures.
Similarly, they empirically recommended the plate screw density should be < 0.3 – 0.4 in simple fractures and < 0.4-0.5 in comminuted fractures.
It is important to note that these recommendations reflected their experience. There were no controls or biomechanical testing to validate these recommendations.

Some small animal breeds like chondrodystrophic breeds have short limb segments that may necessitate compromise of the plate screw density guidelines.

Similarly short segment juxtarticular fractures will necessitate compromise of the plate screw density guidelines.

Gautier and Sommer (2003) use lever theory to show that longer plates loaded in bending produce less pullout force on the screws due to improving the working leverage for the screws. For this reason, they recommend “very long” plates for mechanical advantage.
An example of Class 1 levers would be caudocranial bending on a cranially plated radius fracture where the most distal screw experiences maximal load.
An example of Class 2 levers would be craniocaudal bending on a cranially plated radius fracture where the screw adjacent to the fracture line experiences maximal load.

For humans and animals with long diaphyseal segments, traditional ORIF application of long plates caused considerable soft tissue damage with cosmetic and morbidity consequences. MIO insertion of plates has greatly reduced the soft tissue consequences of long plate application.

When contact / unlocked plates are used screw loading is mainly in pullout and so longer plates could be expected to produce reduced pullout loads on the screws.
When locked plates are used screw loading is mainly in bending rather than pullout. These loads also need to be resisted by the plate.

Trefny (2019, 2024) measured construct stiffness and plate strain in a synthetic oblique Delrin fracture model stabilized with either 6, 8, 10 or 12

hole (equivalent to 40%, 53%, 65% and 80% plate-bone percentage) locked 3.5mm LCPs tested in bending. The 12 hole / 80% plate bone percentage construct was significantly stiffer than the shorter plates and had significantly lower plate strain than the 6 hole / 40% and 10 hole / 65% plates.

In Trefny's study, the oblique fracture gap was fixed at 1.75mm. Applying Gautier and Sommer's guideline for plate span ratio of > 8-10 this would mean a minimum "ideal" plate length of 17.5mm, which is clearly not clinically realistic. So, while plate span ratio is useful as a retrospective outcome measure it is not useful as a prospective decision-making guideline.

Stoffel et al (2003) also found in an FEA model that shorter plates had reduced axial stiffness.

Tornkvist et al (1996) showed that longer plates with wider screw placing more effectively increased construct strength in bridge plating than higher bone screw ratio in shorter plates.

Longer plates have clear biomechanical advantages. By using MIO techniques where practically feasible, long soft tissue approaches can often be avoided for both simple and comminuted fractures, yet still meet the guidelines of "comfortably" long plate bone ratios of > 70%.

What number of screws in each major fragment is appropriate?

There has been a clear trend towards lower plate screw densities that has necessarily and very appropriately evolved with the increasing use of longer plate bone ratios.
AO Principles have long mandated an ideal minimum of 3 bicortical screws per fracture fragment (pff).

Clinical experience has shown that 2 bicortical screws per fragment is usually effective in simple fractures *provided* that they have been compressed and full load-sharing has been achieved.

Gautier and Sommer state that 2 screws should *only* be used in a bone segment when 2 conditions are met; good bone quality and where all the screws are inserted correctly. They conclude that for "safety reasons", a minimum of 3 screws per main fragment is recommended.

Stoffel et al (2003) found that >3 screws pff had little effect on improving axial stiffness and that >4 screws did not significantly increase torsional stiffness. This finding seems to be commonly misinterpreted. Four screws pff achieves the maximum biomechanical effect, assuming good bone quality. Four screws pff resists torsional loads better than 3 or less screws. Three screws pff resist axial and bending loads better than 2 screws.

How can we use this information? In challenging biomechanical situations (poor biomechanical assessment), the ideal goal should be 4 screws pff or

equivalent. In fractures with good biomechanical assessment, the goal should be to achieve 3 screws pff. Two screws pff should not be considered as the norm, but rather as an exception driven by limited bone stock, but only acceptable where compressed anatomic load-bearing reconstruction and perfect screw placement is achievable.

What distribution of screws in each major fragment is appropriate?

The distribution of locked screws within the bone segment will determine the working length of the plate. Working length has been shown to be the **main** determinant of biomechanical performance of plated fracture constructs and is a key decision-making consideration for a surgeon preoperatively.

Unfortunately, misinterpretation of the current literature regarding the effect of plate working length on construct stiffness and plate strain has led to some degree of misunderstanding.

Stoffel et al (2003) showed that plate working length was the most important factor affecting axial stiffness and torsional rigidity. Omitting 1 screw either side closest to the fracture gap resulted in a 60% decrease in axial stiffness and a 34% decrease in torsional stiffness. For every additional hole that was left vacant, thereby increasing the working length, construct stability decreased by about 10% each time.

It is important to consider that decreasing construct stiffness increases both interfragmentary motion and implant deformation. This increases interfragmentary strain and increases implant strain.

If interfragmentary strain exceeds the requirement to produce fibrous tissue, then fracture gap resorption is necessary as the only mechanism possible to reduce strain to a level where fibrous tissue production is sustainable as part of indirect fracture healing. While this is a normal part of indirect or callus healing, the time to complete this process to achieve an anabolic strain environment, increases the number of cycles on the implant.

Implant strain is a measurable surrogate of implant stress and is increased with reduced implant stiffness which creates greater implant deformation. A common misconception is that increasing implant stiffness by decreasing plate working length “concentrates” or magnifies strain across the fracture gap. There is abundant evidence that this is not the case.

Stoffel recommended that for fractures with large fracture gaps such as comminuted fractures, screws should be placed “as close as practicable to the fracture”.

Stoffel also found that in small gap fractures (6mm), where fragment contact did not occur on loading, only the shortest possible working length did *not* fail on cyclic loading to 1 million cycles. When even 1 or 2 screws were removed

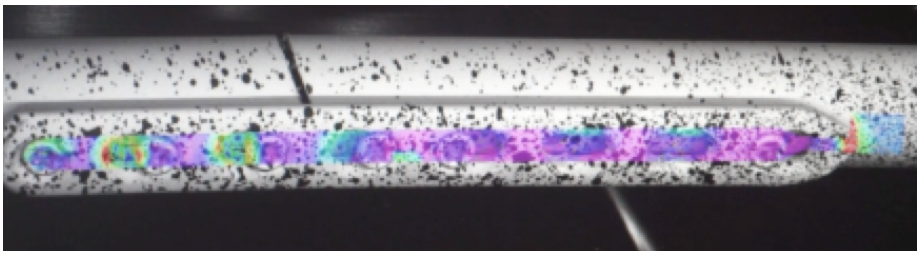
on either side of the fracture to increase the working length, fatigue failure occurred significantly earlier and constructs withstood less than half the cycles of the short working length constructs.

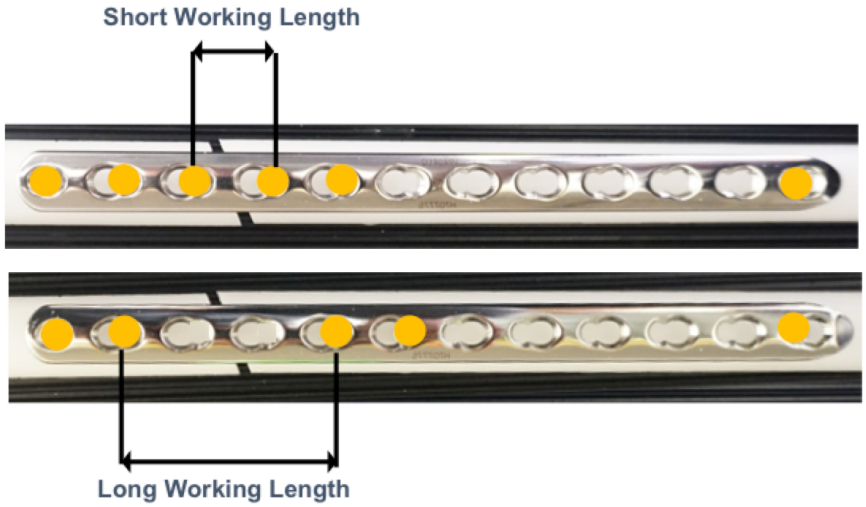
Stoffel used FEA to model the effect of working length on plate stress in a comminuted fracture model with a 6mm gap and a simple fracture model with a 1mm gap.
They found that increasing the working length in the comminuted fracture model by omitting 1 screw either side adjacent to the fracture increased plate stress by 133%.
Conversely, and rather surprisingly, they found that increasing the working length in the 1mm gap model by omitting 1 screw either side adjacent to the fracture reduced plate stress by 10% and omitting 2 screws reduced plate stress by 45%. The reason for this paradoxical decrease in plate stress was that the decrease in stiffness produced by screw omission allowed bone contact, which created a load-sharing situation. While this might seem to be useful from a clinical perspective, it is important to remember that this amount of cyclic instability in a clinical case would almost certainly create intolerably high interfragmentary strain and initiate bone resorption at the fracture gap to reduce interfragmentary strain. Bone contact at the transcortex in small gap fractures creates, by definition, 100% strain which precludes bone healing and drives bone resorption in the only possible option to reduce interfragmentary strain.

The clinical outcome of this would vary from individual to individual though and would be greatly influenced by the biological capacity of the animal and the ultimate strength of the implant. In young animals with a high biological capacity, the process of bone resorption to decrease interfragmentary strain and enable production of fibrous tissue in the fracture gap happens quickly and so fatigue failure is unlikely. In animals with a fracture with a poor biological assessment such as a distal radius fracture in an adult toy breed dog, this process is typically slow, and the consequent prolonged healing now may challenge the fatigue life of the implant.

Trefny (2019, 2024) also investigated the effect of plate working length on construct stiffness and plate strain using 3D DIC (digital image correlation pictured below) in a synthetic short oblique Delrin fracture model stabilized with a 12 hole 3.5mm LCP (pictured below). Being a short oblique fracture, this is not a compressible fracture and so is equivalent to the 1mm gap model that Stoffel investigated with finite element modelling.

Omitting a single screw either side adjacent to the fracture to increase plate working length significantly reduced construct stiffness and significantly increased plate strain at all but one plate region. At no plate location was plate strain reduced by increasing the working length.





Bird et al (2018) also investigated the effect of plate working length on construct stiffness and plate strain using 3D DIC (digital image correlation) in a synthetic compressed transverse fracture model stabilized with either 2mm LCP or a 2mm Notched head T plate. Having screws adjacent to the fracture line created short working length constructs. Longer working length constructs were created by omitting 1 of the screws adjacent to the fracture line and replacing it with a screw 4 holes from the fracture line.

For both plate types, increasing the working length significantly reduced both bending stiffness and torsional stiffness of the constructs. The increased working length also significantly increased plate strain at the majority of locations. At no plate location did increasing the plate working length decrease plate strain.

Maxwell et al (2009) investigated the effect of plate working length on plate strain in DCP and LC-DCP plates in a synthetic Delrin fracture model with a 10mm gap. They found that increasing the working length did not reduce plate strain at the fracture gap but did increase plate strain at the 2 other measure locations.

Mardian et al (2015) in a human FEA study showed that increasing the working length in a 10mm gap model significantly increased interfragmentary motion. They stated that plate working length, defined by screw location, dominated over other aspects of screw placement regarding interfragmentary motion.

Gautier and Sommer recommended in compression plating of simple fractures that the 2 middle plate screws can be inserted as close as possible to the fracture, with the peripheral screws inserted at each plate end.

In situations where plate working length is necessarily long, for example in MIO plating where for biological reasons screws will only be placed at either end of the plate, strategies to limit the likelihood of acute overload failure or cyclic failure of the implant should be considered. Pearson et al (2016) showed that for plates with long working lengths, plate strain could be significantly reduced by the addition of an IM pin of 30-40% of the medullary diameter.

What is the biomechanical effect of increasing plate stand-off from the bone?

Plate-bone "stand-off" is the distance the plate is above the bone surface. This has been shown to significantly affect construct stiffness.

Ahmad and others (2007) reported earlier plastic deformation and lower load to failure in 4.5 mm LCP constructs with a 5 mm plate bone distance. Yang et al (2018) and Ma et al (2013) have shown that increasing plate-bone distance results in lower construct stiffness in both axial compression and torsion.

Evans et al (2021, 2024) evaluated the interaction between working length and plate-bone distance using 2mm LCP as bridge plates in a 6mm synthetic fracture gap model. Three different working lengths were tested with 3 different stand-off distances. They found that increased plate working length reduced construct stiffness in bending and torsion, while increased plate-bone distance reduced construct stiffness under torsional load but not under bending load. They concluded that minimizing working length increased construct stiffness but where a longer working length is unavoidable, such as in heavily comminuted fractures, minimizing stand-off will maximise torsional stiffness.

Learning summary - key points:

- Plate size for an individual animal should be based on thorough fracture assessment.
- Longer plates (plate-bone ratio of >70% have clear biomechanical advantages over shorter plates. Longer plates are stiffer, stronger, have reduced plate strain and produce lower screw pullout loads.
- In animals with long limb segments, MIO strategies to enable long plate placement without an unnecessarily long surgical approach are ideal.
- A minimum of 3 screws per fracture fragment is ideal. Four screws per fracture fragment will provide the maximum resistance to torsional

loads and should be the goal in fractures with a poor biomechanical assessment.

- In fractures with short juxtarticular segments where placement of 3 screws is not possible, placement of 2 screws may be adequate provided compressed load-sharing is achieved and the screws have been correctly inserted.

- Screw density is recommended to be <0-3-0.4 in simple fractures and < 0.4-0.5 in comminuted fractures though this is of questionable decision-making benefit. The plate screw density is more likely to be determined by the individual case particularly regarding the type of fracture, overall diaphyseal length and the lengths of the main fracture fragments. Appropriate plate screw density will result from placement of a comfortably long plate, an ideal minimum of 3 screws per fragment and creation of an appropriate plate working length.

- Regarding screw distribution, plate working length is the most important determinant of construct stiffness, plate strain and interfragmentary motion. Increasing the plate working length by omitting screws adjacent to the fracture reduces construct stiffness, increases interfragmentary motion, and does *not* reduce plate strain.

- The addition of adjunctive fixation such as IM pins or second plates should be considered in bridge plating where either acute or cyclic loads may exceed the implant capacity.

- In fractures where healing time is expected to be prolonged and load-sharing is not possible, or where postoperative activity may be uncontrolled, adjunctive fixation strategies to reduce the likelihood of implant failure are recommended.

- Plate working length has a more significant effect on construct stiffness than plate-bone stand-off. In cases where a longer working length is unavoidable, minimizing stand-off will maximise torsional stiffness.

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