

A Review of the Biomechanical Role of a Unilateral External Fixator in the Fracture Repair Process

Mohammad Kamran Shahid* and Shahbaz Malik

Department of Orthopaedic Engineering, University of Cardiff, Wales, United Kingdom

*Corresponding Author: Mohammad Kamran Shahid, Department of Orthopaedic Engineering, University of Cardiff, Wales, United Kingdom.

Received: February 03, 2016; Published: February 27, 2016

Abstract

A unilateral external fixator comprises of a collection of pins, clamps and sidebars to form a construct on one side of the limb that can be used to stabilise bone fractures and promote healing. An external fixator can allow the operator to alter the flexibility of the fixation. In the presence of flexible fixation, fracture healing happens through the creation of callus, which mechanically joins the bone together. There are 4 stages to this secondary bone fracture healing to include: inflammation, soft callus, hard callus, and remodelling stages. Excessive movement at the fracture site can predispose to non-union and creation of fibrocartilage. However, movement at the fracture site is necessary to stimulate the repair process in the early stages and the magnitude of strain at the site of healing has a role in predicting the tissue type created e.g. fibrocartilage or bone. The strain (ϵ_{Strain}) at the fracture gap is given by the relationship:

$$\epsilon \text{ Strain} = \Delta g / g_0$$

This is calculated from the change in size of the fracture gap (Δg) from the applied force divided by the original size (g_0).

The stiffness of the external fixator should not be excessive because in such conditions, it would protect the bone fracture from the necessary stresses to promote healing. The stiffness of the external fixator is influenced by the load distribution between the external fixator and bone, the pin number and diameter, pin design, pin distance, pin angulation, number of connecting bars, the type of external fixator, and distance between the bone and bars. An ideal external fixator, would have sufficient load distribution between the bone and external fixator, utilise a greater number of fully threaded pins (angulated towards the fracture) in each bone fragment of a diameter (not exceeding 1/3 the diameter of the bone) and have accompanying carbon bars fixed close to the skin and of the shortest length. This construct should provide sufficient stability and stiffness and reduce stress between the pin and bone to prevent failure

The ideal environment for bone fracture repair involves direct contact of the bone fracture ends, axial compression and increased rigidity of the fixation. The fixation used should have a rigidity ranging from 20-60% of the normal bone in the bending state to promote bone stability and healing. This review paper evaluates our current understanding of the biomechanical environment provided by an external fixator in the fracture healing process.

Keywords: External fixator biomechanics; Fracture healing

Introduction

An external fixator comprises of a number of pins that are fixed to bone with numerous clamps and sidebars, which attach to form a construct allowing significant variability (Tencer 2006). It has an important role in fracture fixation as they cause limited damage to the soft tissues and neurovascular structures in comparison to internal fixation using plates. Goatokis and Naravan (2007) describes that it can be used in the trauma situation for definitive management, or allow time for soft tissue problems to be addressed prior to internal fixation. There are many different types to include the unilateral external fixator, which is one placed on one side of the limb (Fragomen

Citation: Mohammad Kamran Shahid and Shahbaz Malik "A Review of the Biomechanical Role of a Unilateral External Fixator in the Fracture Repair Process". *EC Orthopaedics* 3.1 (2016): 254-260.

and Rozbruch 2007). Such fixators can ensure that the limb continues to be functional and ensures stability for the fracture. Unilateral external fixators can take two forms:

- A. An external fixator that has been pre-made but allows change to enable a fracture to be reduced and dynamisation.
- B. An external fixator that is made from a selection of components after pins have been inserted allowing greater variability to the design constructs to address the clinical problem. (Goatakis and Naravan 2007).

Unilateral external fixators can create a mechanical environment that can vary in biomechanical properties due to the variability in the construct of the external fixator. This assignment will look at how such devices can influence the fracture repair process.

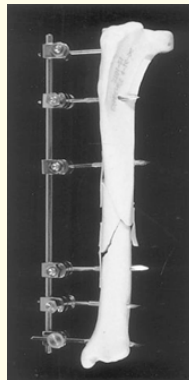


Figure 1: A unilateral External Fixator used here for fracture management (Slatter 2002).

Material and Method

The review of literature was performed through the PubMed database and used key words including: 'external fixator', 'external fixator biomechanics', and 'fracture healing'. The exclusion criteria included: articles not in English and where there was no mention of biomechanics in the article. Materials also accessed were referenced online tools for information and clinical and anatomical text books.

Results and Discussion

The review of literature was performed through the PubMed database and used key words including: 'external fixator', 'external fixator biomechanics', and 'fracture healing'.

Fracture healing

Bone healing of a fracture can be classified as primary or secondary. Palmer, *et al.* (1992) describes primary bone healing where there is no formation of callus and requires absolute stability with or without compression of the bone ends. This contrasts to secondary bone healing where there is formation of callus. Callus forms due to the fixation not allowing sufficient reduction of the fracture so bone ends in the gap are not within close proximity enough to induce direct placement of bone (Palmer, *et al.* 1992).

An external fixator permits the operator to have a role in altering the flexibility of the fixation. Ruedi and Murphy (2000) describe that bone healing in the presence of flexible fixation happens through the creation of callus, which mechanically joins the bone together. They describe that a flexible fixation can allow the fractured bones to displace under the influence of a load over the fracture site. Therefore as the load is increased, elastic deformation is initially observed, where once the load is removed, the fracture ends return to the normal position (Callister 2007). When the load is increased above the ultimate tensile stress, plastic deformation is observed where the fracture bones stay permanently displaced. External fixation can be observed to act as a splint and although load can increase displacement, this can decrease based on the rigidity of the construct (Ruedi and Murphy 2000).

We will look at secondary bone healing here which has 4 stages to include: inflammation, soft callus, hard callus, and remodelling (Ruedi and Murphy 2000):

1. Inflammation stage: Initially post fracture, the fracture site fills with blood and the broken bone ends demonstrate necrosis (Dandy and Edwards 1998). This haematoma is infiltrated with inflammatory cells e.g. macrophages and is slowly transformed to granulation tissue. Osteoclasts have a role by removing the dead bone (Ruedi and Murphy 2000).
2. Soft Callus stage: Approximately 2-6 weeks post fracture, soft callus forms (Dandy and Edwards 1998). This is marked by fibrous tissue forming in place of the haematoma and characterised by a significant increase in blood supply to the fracture callus and marked cellularity (Ruedi and Murphy 2000). Dandy and Edwards (1998) describe that the callus forms around the bone underneath the perisoteum and contains chondroblasts between the fracture ends.
3. Hard Callus stage: This is characterised by mineralisation of the fibrous tissue and fibrocartilage leading to creation of bone, which can take months to occur (Palmer, *et al.* 1992). It begins in an area distant from the fracture site and slowly progresses towards this area.
4. Remodelling stage: Occurs months to years after the fracture has solidified up until the bone architecture returns to its original prior to fracture. Ruedi and Murphy (2000) describe that the cancellous bone is transformed into lamellar bone over time.

Nordin and Frankel (2001) describe that excessive movement at the fracture site can predispose to non-union and creation of fibrocartilage tissue. However there is a certain threshold of movement or micromotion that can act as a stimulator for the healing process. Jagodzinski and Krettek (2007) argue that movement has a positive role in healing during the early stages but can inhibit healing during the later stages. It is thought that the magnitude of strain at the site of healing has a role in predicting the tissue type created e.g. fibrocartilage or bone and is currently under investigation (Nordin and Frankel 2001).

Mechanical Environment for External Fixator

An ideal external fixator should not be excessively stiff, as then the fracture would be protected from the necessary stresses to promote healing (Bucholz, *et al.* 2006). The ideal stiffness required is unknown but the ideal amount necessary for fracture stability and promoting bone healing changes as the fracture heals. Bucholz, *et al.* (2006) further describes that the stiffness should be sufficient to overcome the forces a patient is subjected to during mobilisation to prevent fracture displacement. Bone healing can be achieved by external fixation under close observation and may involve changing the stiffness of fixation during the treatment course. The stiffness of the external fixator is influenced by the load distribution between the external fixator and bone, the pin number and diameter, pin design, pin distance, pin angulation, number of connecting bars, the type of external fixator, and distance between the bone and bars (Palmer, *et al.* 1992).

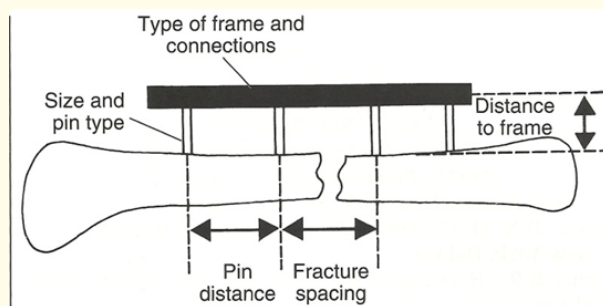


Figure 2: External fixator demonstrating some of the variables that can influence stiffness (Nordin and Frankel 2001).

Load Distribution between bone and external fixator

When an external fixator is in use, there can be a difference in the amount of load distributed between the external fixator and the bone. If there is a fracture that has been reduced satisfactorily and the fracture site is compressed, then a significant magnitude of the ground reaction force (assuming lower limb bone with weight bearing status) can be distributed axially through the bone (Palmer, et al. 1992). In an ideal situation, there needs to be sufficient sharing of the load between the external fixator and bone to help reduce the stress between the bone and pins. There are situations where compression cannot occur e.g. comminuted fractures, and so the ground reaction force is transmitted from the bone to the external fixator via its components. Nordin and Frankel (2001) describe that in such situation, bone resorption is likely to occur due to the “unloading of bone around the device”. This is thought to follow Wolff’s Law which describes that remodelling of bone occurs determined by the mechanical forces it experiences (Wolff 1892). There can be situations where partial-load sharing occurs, especially when fractures are oblique where the external fixator neither compresses nor holds the 2 fracture ends apart (Palmer, et al. 1992). Such situations are demonstrated in Figure 2.

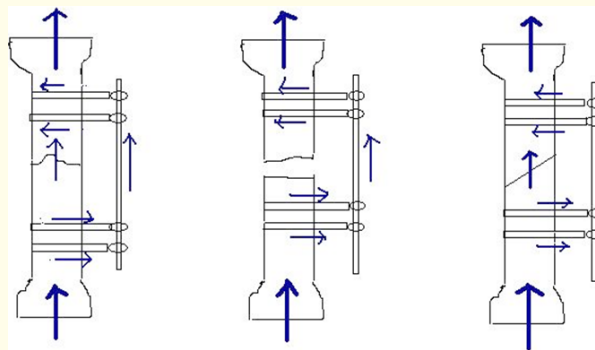


Figure 3: External fixator demonstrating 3 situations whilst stabilising midshaft tibia fracture: ideal load sharing fixation; nonload sharing fixation; and partial load-sharing fixation (left to right). Arrows show transmission of the the ground reaction force. (Palmer, et al. 1992).

Number of Pins

As the number of pins used is increase, the overall stiffness of the external fixation to bone is increased because there is now sharing of the forces that act upon it amongst the pins leading to decrease stress at each pin (Moss and Tejwani 2007). However, this cannot be ideal in scenarios where there is non-load sharing as studies show that plastic deformation occurs of the connecting bar at the region of the fracture site at increased axial compressive loads (Palmer, et al. 1992). Therefore in such cases it was found that increasing pin number from 2 to 4 for each bone piece, it did not increase the stiffness of the external fixator whilst utilising 1 bar. Palmer, et al. (1992) describes that as we increase the number of pins to 4 for each bone piece in this case, whilst utilising 2 bars, one can increase the “axial compressive stiffness” of the fixator by a factor of 2.

Pin Diameter

Moss and Tejwani (2007) describe that the diameter of a pin can influence stiffness, which is directly proportional to the radius⁴. Therefore as we increase the pin diameter from 3 to 6mm, the stiffness increases by a multiple of 16. Hence, the largest pin diameter should be considered that is less than 1/3 the bone diameter to decrease risk of pin-hole fractures (Moss and Tejwani 2007).

Pin Design

The pin design is important as there is significant stress at the junction between the pin and bone in the external fixator construct, which can be responsible for early loosening of the pin and failure. Palmer, et al. (1992) describes that threaded pins are more likely to grip the bone with respect to unthreaded ones and are more stiff. However, when taking pin diameter into account, it is noted that

Citation: Mohammad Kamran Shahid and Shahbaz Malik “A Review of the Biomechanical Role of a Unilateral External Fixator in the Fracture Repair Process”. *EC Orthopaedics* 3.1 (2016): 254-260.

threaded pins are less stiff than non-threaded pins of the same outer diameter and so this need to be accounted for in determining the ideal pin design. Bindra (2005) describes that pins are now constructed with a larger core diameter but less core-thread diameter distance to allow the pin to sustain bending forces. Therefore when the pin is fixed to both cortices, forces causing the pin to pull out act mainly at the distant cortex and bending forces at the near cortex. Hence, an ideal design suggested is a short threaded pin inserted into both cortices where the thread holds the far cortex and the wider shaft holds the near cortex (Bindra 2005).

Pin Distance

The distance between the pins in each bone piece and from the fracture affects the stiffness of the construct. Palmer, *et al.* (1992) describes the relationship of the bending stiffness of the connecting bar being inversely proportional to its length³. This means that one can ensure that the bar is shorter by inserting pins near the fracture and so obtaining more stiffness. Placement of pins too close to the fracture may introduce bacteria from the external environment and so pin placement needs careful thought and planning. The other pins should be equally placed within each bone piece to maintain stability at the fracture site.

Pin Angulation

The angle of insertion of pins into the bone can increase the stiffness of the external fixator construct. Approximately 20 degrees of angulation towards the fracture on either side can increase the stiffness of the fixator and is associated with a lower chance of pin loosening (Palmer, *et al.* 1992)

Connecting Bars

Connecting bars act as a bridge between the pin sites to hold and maintain stability of the external fixator. Kowalski, *et al.* (1996) discovered that bars made of carbon were 15% more stiff than stainless steel types which became plastically deformed when given a bending moment of 2250 Nm. As carbon bars demonstrated elastic deformation during testing, the recommendation is to use these over the stainless steel types. The use of 2 bars to the fixation has the added advantage of increasing strength by up to 2 fold against axial compression and plastic deformation of the bar and pins (Palmer, *et al.* 1992). It has also been shown that by use of 2 connecting bars, one can improve bending stiffness by 20% in both the ipsilateral plane and at 90 degrees to the external fixator (Behrens and Johnson 1989)

Type of external Fixator

We have been restricted to looking at the unilateral external fixator in this assignment, which is placed on one side of the limb. There are variations of this unilateral fixation in terms of one plane or 2 plane configurations. To achieve a 2 plane external fixator, a new external fixator is applied but at 90 degrees to the previous one. Moss and Palmer, *et al.* (1992) have showed that the 2 plane fixation has greater strength against axial compression and torsional forces.

Distance between bone and Bars

The bar should be positioned in close proximity to the skin in order to reduce the pin working length. Palmer, *et al.* (1992) describes that this can result in stress reduction between the pin and bone and reduce the chance of pin failure.

Biomechanics of fracture healing

The ideal environment for bone fracture repair involves direct contact of the bone fracture ends, axial compression and increased rigidity of the fixation (Lucas, *et al.* 1998). Lucas, *et al.* (1998) describes that both the fracture gap size and the influence of movement at the fracture site can determine the tissue that is created there. Figure 4 demonstrates the strain in the fracture gap of bone stabilised with external fixator, with a superimposed exaggerated gap created due to the action of a force.

Strain can be calculated from determining the change in size of the gap from the applied force divided by the original size (Callister 2007). Lucas, *et al.* (1998) describes in Table 1 that for a given gap size, the type of tissue that can be predicted to form within the fracture gap at variable strain ranges

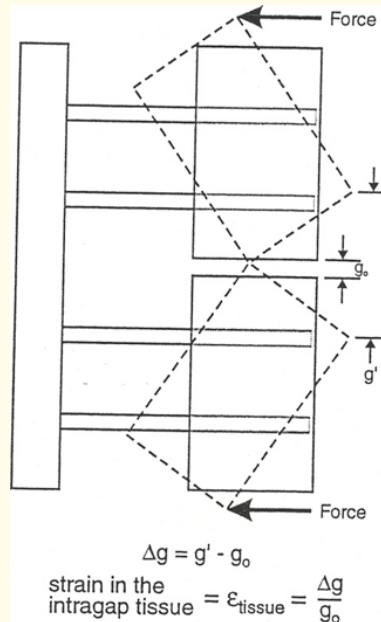


Figure 4: A bone stabilised by external fixator with a superimposed picture of exaggerated displacement from the action of force shows the strain in the fracture gap ($\Delta g/g_0$) formulated from the initial gap size and displacement gap size (Lucas., et al. 1998).

Strain at Fracture gap (%)	Tissue Predicted
10-100	Granulation tissue
2-10	Fibrocartilage
2	Bone

Table 1: The tissue predicted within the fracture gap for different strain ranges at the gap. (Lucas., et al. 1998).

In environments where strain is greater than 10%, the granulation tissue that forms closing the space at the fracture site, can subsequently reduce the strain, allowing fibrocartilage or bone to be created. However, Lucas., et al. (1998) describes that if the threshold of strain exceeds that of the tissue created, it can lead to further injury resulting in the formation of a pseudoarthrosis.

The overall objective is to reduce the fracture as best as possible and to regulate the movement at the fracture gap to ensure that healing occurs with bone and so there are no preceding steps. The external fixator should stabilise the fracture to have a stiffness or rigidity between 20-60% of the normal bone in the bending state (Lucas., et al. 1998).

Conclusion

A unilateral external fixator can create a mechanical environment to help heal bone fractures typically by secondary bone healing in suitable patients. It can allow the operator to alter the flexibility of the fixation allowing healing to occur through the formation of callus. Movement up to a certain threshold at the fracture site can have a bone healing promoting effect in the early stages and the magnitude of strain at the bone healing site, can predict the tissue type created. The strain (ϵ Strain) at the fracture gap is given by the relationship:

$$\epsilon_{Strain} = \Delta g/g_0 \quad (\text{Lucas., et al. 1998})$$

This is calculated from the change in size of the gap (Δg) from the applied force divided by the original size (g_0).

The ideal environment for bone fracture repair involves direct contact of the bone fracture ends, axial compression and increased rigidity of the fixation (Lucas, *et al.* 1998). The fixation used should have a rigidity ranging from 20-60% of the normal bone in the bending state to promote bone stability and healing.

An ideal external fixator should not be excessively stiff as then this situation would protect the fracture fixation from the necessary stresses that would promote healing. The stiffness of the external fixator is influenced by the load distribution between the external fixator and bone, the pin number and diameter, pin design, pin distance, pin angulation, number of connecting bars, the type of external fixator, and distance between the bone and bars (Palmer, *et al.* 1992). Such variations in the external fixator can all contribute to creating the ideal mechanical environment to allow healing if used in expert hands.

Bibliography

1. Behrens F and Johnson W. "Unilateral External Fixation. Methods to increase and reduce frame stiffness". *Clinical Orthopaedics and Related Research* 241 (1989): 48-56.
2. Callister WD. "Materials Science and Engineering An Introduction". *New York: John Wiley and Sons.* (2007).
3. Dandy DJ and Edwards DJ. "Essential Orthopaedics and Trauma". *London: Churchill Livingstone* (1998).
4. Fragomen AT and Rozbruch SR. "The Mechanics of External Fixation". *The musculoskeletal Journal of Hospital for Special Surgery* 3.1 (2007): 13-29.
5. Goatokis N and Narayan B. "Stability with unilateral external fixation in the tibia". *Journal of strategies Trauma Limb Reconstruction* 2.1 (2007): 13-20.
6. Jagodzinski M and Krettek C. "Effect of mechanical stability on fracture healing-an update". *Injury* 38.1 (2007): S3-10.
7. Kowalski M., *et al.* "Comparative biomechanical evaluation of different external fixation sidebars: Stainless-steel tubes versus carbon fiber rods". *Journal of Orthopaedic Trauma* 10.7 (1996): 470-475.
8. Lucas GL., *et al.* "A primer of Biomechanics". *Germany: Springer Verlag* (1998).
9. Moss DP and Tejwani NC. "Biomechanics of External Fixation". *Bulletin of the NYU Hospital for Joint Diseases* 65.4(2007): 294-299.
10. Nordin M and Frankel VH. "Basic Biomechanics of the Musculoskeletal System". Philadelphia: Lippincott Williams and Wilkins.
11. Palmer RH., *et al.* "Principles of bone healing and biomechanics of external fixation". *Veterinary Clinics of North America: Small Animal Practice* 22.1 (1992): 45-68.
12. Ruedi TP and Murphy WM. "AO Principles of Fracture Management. New York: Thieme Stuttgart.
13. Slatter DH. "Textbook of small animal Surgery". Philadelphia: WB Saunders (2002).
14. Tencer AF Biomechanics of Fixation and Fractures. In: Bucholz RW. eds. *Rockwood and Green's Fractures in Adults.* 6th ed. Philadelphia: Lippincott Williams and Wilkins (2006): 4-38.
15. Wolff, J. 1892. *Das Gesetz der Transformation der Knochen.* Berlin: Hirschwald.

Volume 3 Issue 1 February 2016

© All rights are reserved by Mohammad Kamran Shahid and Shahbaz Malik.