Bone fracture healing under Ilizarov fixator: Influence of fixator configuration, fracture geometry, and loading

Received: 5 December 2018 | Revised: 17 February 2019 | Accepted: 6 March 2019
DOI: 10.1002/cnm.3199

RESEARCH ARTICLE - APPLICATION

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Bone fracture healing under Ilizarov fixator: Influence of fixator configuration, fracture geometry, and loading

Ganesharajah Ganadhiepan[1] | Saeed Miramini[1] | Minoo Patel[2] | Priyan Mendis[1] | Lihai Zhang[1]

[1]Department of Infrastructure Engineering, The University of Melbourne, Parkville, Victoria, Australia
[2]Centre for Limb Lengthening & Reconstruction, Epworth Hospital Richmond, Richmond, Victoria, Australia

Correspondence
Lihai Zhang, Department of Infrastructure Engineering, The University of Melbourne, Parkville, Victoria 3010, Australia.
Email: lihzhang@unimelb.edu.au

Funding information
University of Melbourne

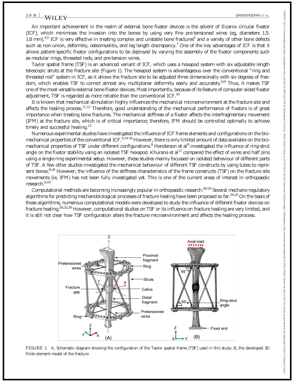
Abstract

This study aims to enhance the understanding of the relationship between Ilizarov fixator configuration and its effects on bone fracture healing. Using Taylor spatial frame (TSF) as an example, the roles of critical parameters (ie, TSF ring diameter, wire pre-tension, fracture gap size, and axial load) that govern fracture healing during the early stages were investigated by using computational modelling in conjunction with mechanical testing involving an advanced 3D optical measurement system. The computational model was first validated using the mechanical test results and then used to simulate mesenchymal stem cell (MSC) differentiations within different regions of the fracture site under various combinations of TSF ring diameter, wire pre-tension, fracture gap size, and axial load values. Predicted spatially dependent MSC differentiation patterns and the influence of each parameter on differentiations were compared with in vivo results, and good agreement was seen between the two. Gap size was identified as the most influential parameter in MSC differentiation, and the influence of axial loading and TSF configuration (ie, ring diameter and wire pre-tension) on cell differentiation was seen to be gap size dependent. Most changes in cell differentiation were predicted in the external callus (periosteal), which is the crucial region of the callus in the early stages. However, for small gap sizes (eg, 1 mm), significant changes were predicted in the endosteal callus as well. The study exhibits the potential of computational models in assessing the performance of Ilizarov fixators as well as assisting surgeons in patient-specific clinical treatment planning.

KEYWORDS
3D optical measurement system, mechanical test, mechano-regulation, mesenchymal stem cell, Taylor spatial frame

1 | INTRODUCTION

Minimally invasive surgical procedures to treat bone fractures have gained interest during recent decades.[1-3] This has led to the evolution of different external fixator devices with variety of capabilities. The main advantage of external fixators over the alternatives is their adjustability of configurations according to how healing progresses and thereby enabling better microenvironments to be achieved at the fracture site throughout the healing process.[3]



An important achievement in the realm of external bone fixator devices is the advent of Ilizarov circular fixator (ICF), which minimises the invasion into the bones by using very fine pre-tensioned wires (eg, diameters 1.5-1.8 mm).[4,5] ICF is very effective in treating complex and unstable bone fractures[6] and a variety of other bone defects such as non-union, deformity, osteomyelitis, and leg length discrepancy.[7] One of the key advantages of ICF is that it allows patient-specific fixator configurations to be deployed by varying the assembly of the fixator components such as modular rings, threaded rods, and pre-tension wires.

Taylor spatial frame (TSF) is an advanced variant of ICF, which uses a hexapod system with six adjustable length telescopic struts at the fracture site (Figure 1). The hexapod system is advantageous over the conventional "ring and threaded rod" system in ICF, as it allows the fracture site to be adjusted three dimensionally with six degrees of freedom, which enables TSF to correct almost any multiplanar deformity easily and accurately.[8,9] Thus, it makes TSF one of the most versatile external bone fixator devices. Most importantly, because of its feature of computer-aided fixator adjustment, TSF is regarded as more reliable than the conventional ICF.[10]

It is known that mechanical stimulation highly influences the mechanical microenvironment at the fracture site and affects the healing process.[11,12] Therefore, good understanding of the mechanical performance of fixators is of great importance when treating bone fractures. The mechanical stiffness of a fixator affects the interfragmentary movement (IFM) at the fracture site, which is of critical importance; therefore, IFM should be controlled optimally to achieve timely and successful healing.[13]

Numerous experimental studies have investigated the influence of ICF frame elements and configurations on the biomechanical properties of the conventional ICF.[4,14-16] However, there is only limited amount of data available on the biomechanical properties of TSF under different configurations.[8] Henderson et al[9] investigated the influence of ring-strut angle on the fixator stability using an isolated TSF hexapod. Khurana et al[17] compared the effect of wires and half pins using a single-ring experimental setup. However, these studies mainly focussed on isolated behaviour of different parts of TSF. A few other studies investigated the mechanical behaviour of different TSF constructs by using tubes to represent bones.[8,18] However, the influence of the stiffness characteristics of the frame constructs (TSF) on the fracture site movements (ie, IFM) has not been fully investigated yet. This is one of the current areas of interest in orthopaedic research.[8,19]

Computational methods are becoming increasingly popular in orthopaedic research.[20-24] Several mechano-regulatory algorithms for predicting mechanobiological processes of fracture healing have been proposed so far.[24,25] On the basis of these algorithms, numerous computational models were developed to study the influence of different fixator devices on fracture healing.[20,22,26] However, computational studies on TSF or its influence on fracture healing are very limited, and it is still not clear how TSF configuration alters the fracture microenvironment and affects the healing process.

FIGURE 1 A, Schematic diagram showing the configuration of the Taylor spatial frame (TSF) used in this study; B, the developed 3D finite element model of the fracture

Philip Frederik Ligthart

Dept of Mech & Mechatronic Eng,
Stellenbosch University, South Africa

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- Necessary background
- Talk focus
- General model
- Numerical model
- Validation
- Parametric study
- Insights

Bone fracture healing

Primary bone healing

- Every day process
- Requires absolute stability

- Plate fixation
- Intramedullary nailing

Secondary bone healing

- Occurs with relative stability
- Involves callus formation - new bone

- External fixation

Secondary bone healing

- Bone ends are not in direct contact
- Relative motion between bone ends - Interfragmentary movement (IFM)
- Bone healing is influenced (theories) by Interfragmentary strain (IFS)

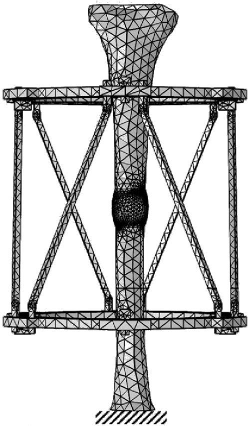
- Found 10 different mechanoregulation measures in literature

Generally, 2–10 % engineering strain is desired

Ilizarov fixator

- Circular rings
- Tensioned wires - k-wires - 1.5–1.8 mm
- Half pins - Schanz screws - 3–6 mm
- Threaded rods

Taylor Spatial Frame (TSF)



Focus of the talk

Input		Function		Output
Broken Bone	→	Fixation configuration	→	Bone healing

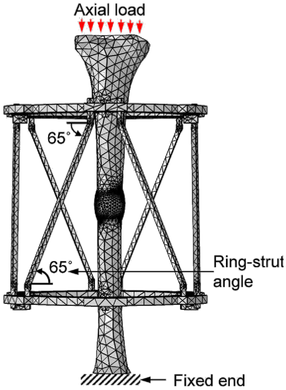
General model setup

The same general model setup was used simulation and experimental validation

- CT scan of a human tibia used
- Perpendicular k-wires
- Strut angle of 65° remained constant
- Bones centred in the rings

Finite element model

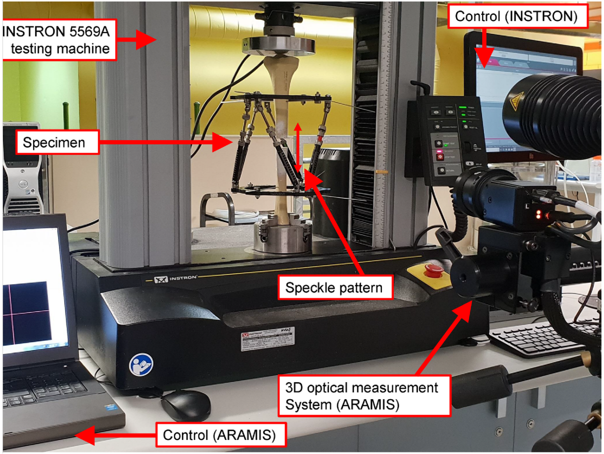
- Homogeneous, linear elastic material properties
- Axial load applied as a point load
- Geometric non-linearity included for strain stiffening of k-wires
- Bone k-wire interface modelled using RBE2 elements (or equivalent)



Finite element parameters

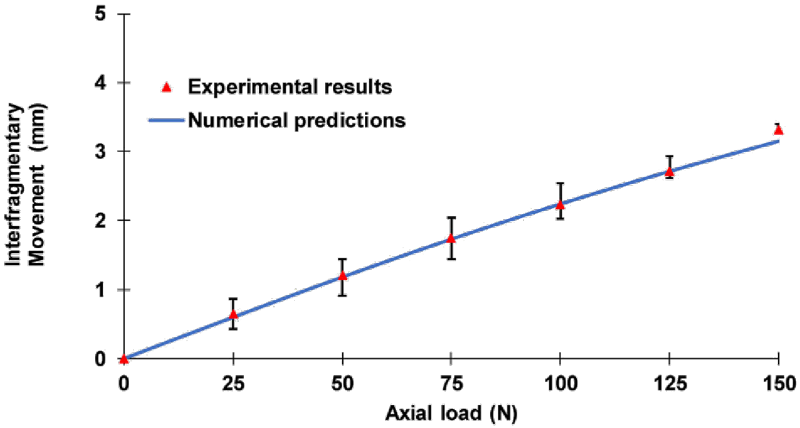
- COMSOL Multiphysics used for the simulations
- Second order tetrahedral elements - all parts
- $\approx 215\,000$ elements
- Convergence criteria:
  - $0.1\,\mathrm{mm}$ for displacement (Absolute)
- Mesh convergence study
  - $\leq 2\,\%$ difference between meshes considered converged

Validation



- Used the ARAMIS DIC system to measure displacements.
- Quote accuracy of 0.0002 mm

130 mm ring



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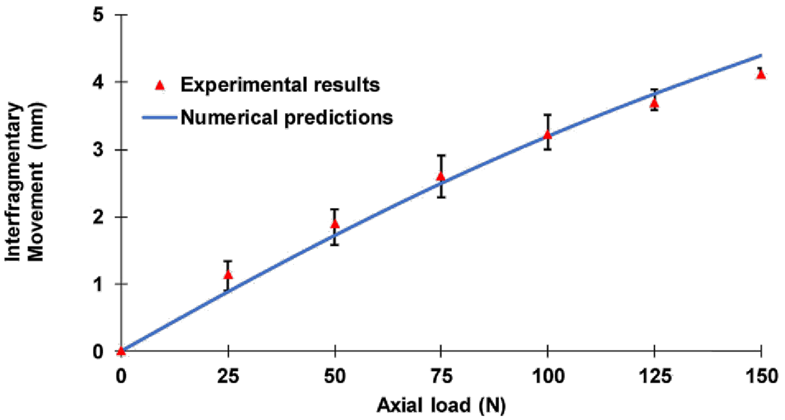
155 mm ring



5
4
3
2
1
0
Interfragmentary Movement (mm)
Experimental results
Numerical predictions
0
25
50
75
100
125
150
Axial load (N)

Parameters

Count	Parameter	Variations
2	Ring diameter	130 and 155 mm
3	K-wire tension	50, 90 and 130 kg
3	Gap size	1, 3 and 5 mm
3	Axial load	100, 150 and 200 kg

Factorial design: $2 \times 3 \times 3 \times 3 = 54$
However: 18 simulations were performed

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Insights

- Found that out of plane motion/torsion is negligible
- Gap size is by far the most influential parameter

Shortcomings

- Previous authors have found slipping between bone and k-wire – not considered
- Loading limits results – could explain the lack of out of plane motion
- Previous authors have shown yielding of k-wires – not considered
- Output measure is not clear – measurable IFM or IFS would be more interpretable
- Increasing stiffness of callus region not considered

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