Biomechanics of Two External Fixator Devices Used in Rat Femoral Fractures

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ABSTRACT: The use of external fixators allows for the direct investigation of newly formed interfragmentary bone, and the radiographic evaluation of the fracture. We validated the results of a finite element (FE) model with the in vitro stiffness' of two widely used external fixator devices used for in vivo analysis of fracture healing in rat femoral fractures with differing construction (Ti alloy ExFix1 and PEEK ExFix2). Rat femoral fracture fixation was modeled using two external fixators. For both constructs an osteotomy of 2.75 mm was used, and offset maintained at 5 mm. Tufnol, served as standardized substitutes for rat femora. Constructs were loaded under axial compression and torsion. Overall axial and torsional stiffness were compared between the in vitro models and FE results. FE models were also used to compare the fracture movement and overall pattern of von Mises stress across the external fixators. In vitro axial stiffness of ExFix1 was 29.26 N/mm ± 3.83 compared to ExFix2 6.31 N/mm ± 0.67 ($p^* < 0.05$). Torsional stiffness of ExFix1 was 47.5 Nmm/° ± 2.71 compared to ExFix2 at 19.1 Nmm/° ±1.18 ($p^* < 0.05$). FE results predicted similar comparative ratios between the ExFix1 and 2 as the in vitro studies. FE results predicted considerably larger interfragmentary motion in the ExFix2 comparing to ExFix1. We demonstrated significant differences in the stiffness' of the two external fixators as one would expect from such variable designs; yet, importantly we validated the utility of an FE model for the analysis and prediction of changes in fracture mechanics dependent on fixator choice. © 2018 Orthopaedic Research Society. Published by Wiley Periodicals, Inc. J Orthop Res 37:293–298, 2019.

Keywords: fracture fixation; finite element analysis; biomechanics

Multiple physiological and mechanical factors govern the fracture healing process. Overall stiffness of the fracture fixation construct directly impacts the axial, torsional, and shear interfragmentary movement at the fracture site.[1–3] These subsequently impact the healing process and as with physiological healing, rigid fixation will lead to intramembranous ossification, while those that are less rigid, allow for the creation of cartilaginous callus and endochonrdral ossification.[4,5]

Rodents have been widely used to investigate the fracture fixation. They are an invaluable animal model used to understand the fracture healing process and to develop new technologies and treatments to address complications such as non-union. A number of external fixators have been used to fix femoral fractures in rodents. These fixators, typically result in a combination of intramembranous and endochondral ossification with studies illustrating healing by various biological scenarios in different models.[6,7]

The literature comparing the biomechanical differences of existing external fixators in rodents is limited. Harrison et al.[8] reported no significant difference in axial stiffness between aluminium and titanium fixator bar materials. However, pin material and thickness does have a large effect on torsional and axial stiffness. Mark et al.[9] reported a 50% decrease in axial stiffness and transverse stiffness of the fixator, when using a 1.0-mm compared to a 1.2-mm outer diameter pin. Willie et al.[10] demonstrated significantly reduced stiffness at the fracture site of titanium alloy pins versus stainless steel in fixators of the same design, with similar effects of body material and offset on stiffness as previous studies. Glatt et al.[11] reported the development of a variable stiffness PEEK fixator where fracture rigidity can be altered during healing. This PEEK fixator is gaining favor for use in the investigation of rodent fracture healing as the four pin construct is lighter than traditional titanium and stainless steel fixators and has been shown to be well tolerated in vivo.[12] In contrast, the majority of studies utilize a more traditional unilateral fixator design such as the Harrison et al. titanium alloy fixator. Recently reported variations of the Harrison fixator utilize two carbon fibre cross bars with four aluminium pins[13,14]; heavier than the Glatt fixator. Therefore, while there is a body of literature on the biomechanics of different external fixators on rodents[15,16] and some variations of them, for example, their material properties and dimensions, to the best of our knowledge, no study has compared the effects of a variable stiffness fixator and a static fixator on the in vitro stabilization of a rat femoral fracture model. These are two different external fixator designs and a direct biomechanical comparison between them lacks in literature and is crucial to advance our understanding of the interplay between the biomechanical and biological factors in the context of fracture healing.

Studies investigating the effect of fixator construct on fracture stabilization can be laborious, necessitating investigation of each design parameter-including

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crossbar number/size/ offset, pin size, and each component material. Subsequently, the ability to utilize computational modeling to determine the mechanical characteristics of any fixator construct, is invaluable. So long as the models are validated using in vivo or in vitro experimental data finite element (FE) modeling provides a unique opportunity to model experimental scenarios computationally and accurately.[17–19] As such, the creation of a validated design tool, that can replicate in vivo biomechanics, allow the augmentation and refinement of fixator characteristics to best suit experimental conditions, and yet does so in a timely and cost effective fashion-would be most beneficial to those working with fracture experimental models.

The aim of this study was to compare the biomechanics of two increasingly utilized rodent external fixators; a derivation of the Harrison et al. titanium alloy fixator, and the Glatt/AO PEEK external fixator, but more importantly to validate an FEA model of design with the ex vivo data. These fixators where chosen specifically in order to attempt FEA validation with two very disparate fixator designs. We utilized a series of experimental in vitro testing and in silico computational models based on FE method.

MATERIALS AND METHODS

External Fixator Designs

The study compared two external fixator designs. The first (ExFix1) has two graphite cross bars of 2×40 mm, spaced 4 mm apart, fixed between two titanium alloy (Ti6Al-4v) blocks. These blocks measured 8 mm in height, 10 mm in width, and 7.2 mm in depth. This design used four titanium alloy threaded pins of 0.8/1.0 mm, fixed within the blocks with stainless steel grub screws. The second fixator (ExFix2) was comprised of a single PEEK crossbar and again four stainless steel threaded pins. The crossbar measured 16.5 mm long, 5 mm wide, and 2 mm deep with four 1 mm holes to locate the steel pins. A single 12.5 mm long, 1 mm wide rectangular opening runs parallel with the openings for the steel pins; again each pin measured 0.8/1.0 mm. The offset as measured from the free length of the pins beneath the crossbar to the upper surface of the bone, was kept constant at 5 mm throughout testing. ExFix1 weighed 6.23 g (range 6.22–6.31 g), and ExFix 2 3.11 g (range 3.08–3.65 g).

A hollowed homogenous rod of laminated Tufnol (Tufnol Composites, Birmingham, UK), of similar elastic modulus to adolescent rat femora (inner diameter 1.5 mm, outer diameter 4 mm, length 35 mm) served as standardized substitute for bone and fixed using ExFix1 ($n = 5$) and 2 ($n = 5$). Fixation was carried out using custom drill guides of 0.8 mm that allowed for the accurate predrilling of holes into the Tufnol, after which pins were manually screwed into position to breach both cortices by one thread. After the fixator was fixed to the Tufnol bone a fracture was created with a 2.75 mm fracture gap maintained.

In Vitro Testing

The Tufnol specimens were tested non-destructively using a Zwick (Zwick-Roell, Germany) materials testing machine to determine axial and torsional stiffness. In compression, a maximum load of 40 N was applied, with a preload of 0.5 N at a rate of 0.5 mm/min. Load was applied onto potted concave ends of the Tufnol via steel beads attached to the testing machine, and the loading-unloading process repeated three times for each sample.

In torsion both ends of the sample were fixed into titanium cylinders with grub screws to negate slipping during testing. One end of the Tufnol remained static, whilst a maximum vertical load of 40 N was applied to the other end with a lever arm of 75 mm, which led to torsion of 3,000 Nmm. Loading was repeated three times per specimen and torsional stiffness was calculated by dividing the applied torque by the degrees of rotation of the proximal end of the Tufnol.

Finite Element Analysis

Computer-aided design models of the bone and two external fixators were developed in CATIA V5 (Dassault Systèmes, Paris FR—Fig. 1). Dimensions exactly reflected those of the real-life fixator models and all parts assigned isotropic material properties; The Tufnol bone model has an elastic modulus of 6.5 GPa and Poisson's ratio 0.4.[20–22] Titanium alloy blocks in the ExFix1 have an elastic modulus of 96 GPa and a Poisson's ratio of 0.36. The Graphite rods have an elastic modulus of 4.1 GPa and a Poisson's ratio of 0.17. The PEEK crossbar of the ExFix2 has an elastic modulus of 3.6 GPa and a Poisson's ratio of 0.38. Finally, stainless steel pins in both fixators were given the same mechanical properties: an elastic modulus of 193 GPa and Poisson's ratio of 0.31. The effect of screw pull-out at the fixator-Tufnol interface was ameliorated by gluing these contacts during experimental testing; subsequently, the interface experienced minimal micro-motion upon loading in vitro and allowed all pin-Tufnol interfaces to be modeled as "fully fixed."

Interfaces such as at the crossbar-pin interface had inherent micro-motion as they were either threaded into position or held with grub screws. Thus two simulations were created, one with all contacts "fully fixed" and a second

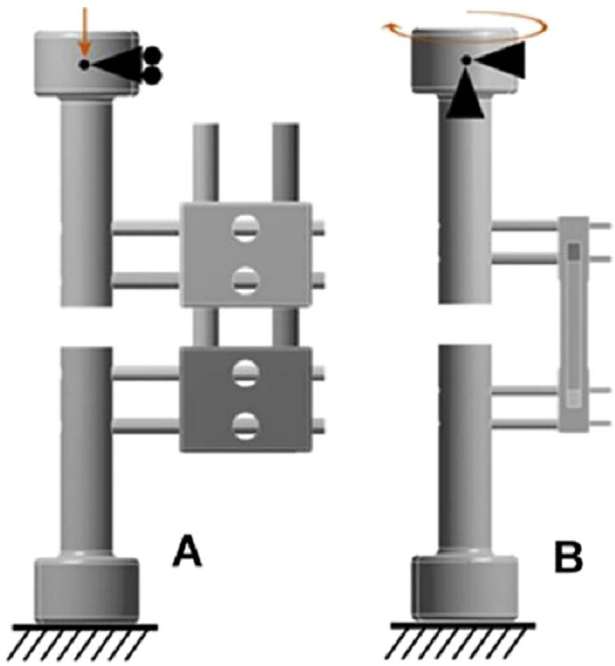

Figure 1. Computer aided designs of both external fixator models, with arrows demonstrating load constraint conditions.

with all grub screws and threaded contacts "relaxed" to account for this motion. The relaxed model used contact elements at the interfaces with a friction coefficient of 0.4.[17] The expectation being that the properties of each fixator would be between these two extreme models.

In order to replicate the boundary conditions of the test rigs, the constraints were applied within the concave housing of the Tufnol under axial loading conditions and along the outside face of the housing under torsional loading conditions. Additionally, the surface/node in which the load was applied was also constrained to translate in only the axis parallel to the line of loading.

Analyses were carried out in FE package ANSYS (Canonsburg, PA). Tetrahedral elements were used to mesh all components of the fixators and Tufnol. Convergence was tested on each fixator by increasing the number of elements from ca. 5,000 to 2,000,000 incrementally. The solution for ExFix1 converged to within 5% at approximately 135,000 elements when measuring axial stiffness and approximately 260,000 elements when measuring torsional stiffness. For ExFix2, the solution converged for both quantities of interest at approximately 322,000 elements. Results converged substantially faster with the use of mid-side nodes, and as such they were used throughout.

In addition to axial and torsional stiffness, FEA was also used to evaluate fracture gap displacement as measured by nodes either side of the osteotomy. Von Mises stresses were calculated for each fixator and the points of maximal stress also determined. It must be noted that since in this study no detail validation of the strain pattern was carried out the stress results were analyzed qualitatively.

Statistical Analysis

Statistical analysis was performed on the experimental data. The ANOVA assumption of normality was tested using the Shapiro–Wilks normality test. If the assumption was met, an ANOVA was performed, if not, a Mann Whitney *U*-test was used. The data were analyzed using Prism 4.03 (GraphPad Software, Inc., La Jolla, San Diego, CA) and a significance level when comparing data was set at $p < 0.05$.

RESULTS

Axial Stiffness

ExFix1 was 29.26 N/mm ± 3.83 compared to ExFix2 6.31N/mm ± 0.67 ($p^* < 0.05$). The fully restricted FEA model predicted axial values of 79.95 and 31.57 N/mm for ExFix1 and 2, respectively. The model under secondary contact conditions produced axial values of 46.12 and 7.52 N/mm, respectively (Fig. 2A).

Torsional Stiffness

ExFix1 was 47.5 Nmm/° ± 2.71 compared to ExFix 2 at 19.1 Nmm/° ±1.18 ($p^* < 0.05$). The fully restricted FEA model predicted torsional stiffness of 98 and 50 Nmm/° for ExFix1 and 2, respectively. The model under secondary contact conditions produced torsional stiffness of 89.8 and 27 Nmm/°, respectively (Fig. 2B).

Comparative Ratios

The ratio of ExFix1: ExFix2, axial and torsional stiffness based on the in vitro experimental data was 4.6 and 2.5, respectively. The same ratio based on the FEA with fully fixed interface conditions were 2.5 (46% lower than the experimental data) and 2 (20% lower than the experimental data) for the axial and torsional stiffness, respectively. The same ratio based on the FEA with relaxed interface were 5.1 (11% greater than experimental data) and 3.3 (32% greater than experimental data) for the axial and torsional stiffness, respectively (Fig. 3).

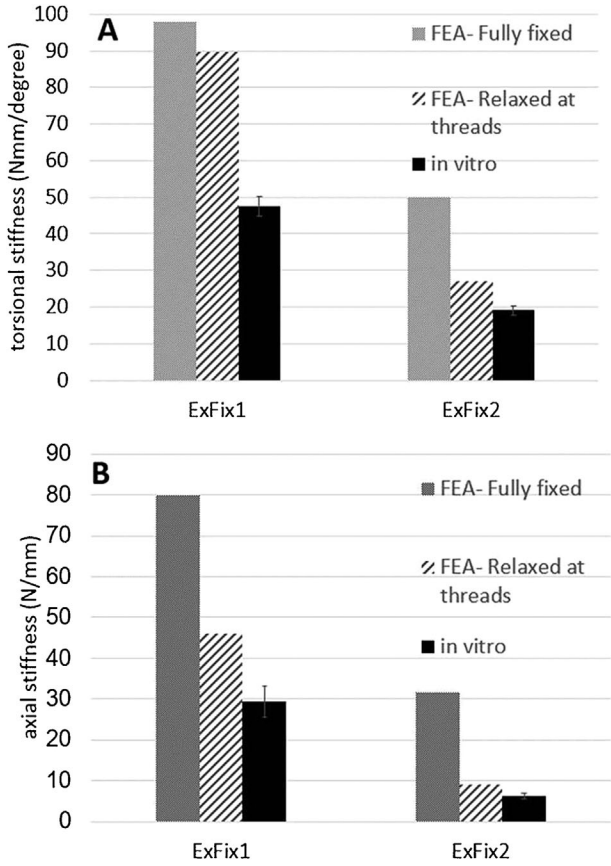

Figure 2. (A and B) Demonstrating the torsional and axial stiffness' of both external fixators in vitro and in silico.

Fracture Movement

Total fracture movement as measured in the FE models, was greater for ExFix2 in all planes versus

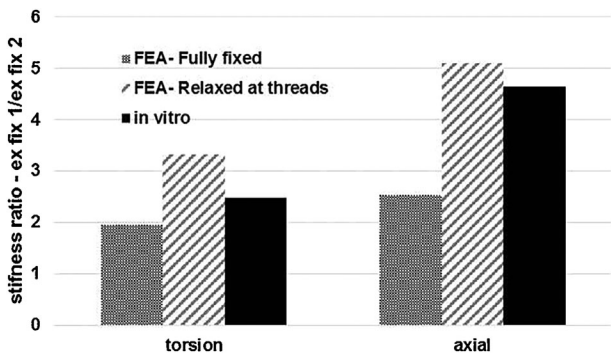

Figure 3. Demonstrating the comparative stiffness ratios in torsion and compression for in vitro and in silico testing.

ExFix1. Less than 1 mm of movement occurred with ExFix1 at the maximal loading however, in the ExFix2 the fragments come into contact leading to a fracture movement of about 2.7 mm based on the relaxed interface model. Under axial loading ExFix1 was found to have 0.54 and 0.91 mm of movement with the fully fixed and relaxed models. Whereas ExFix2 demonstrated 1.49 and 2.75 mm of movement respectively. Under torsional conditions, ExFix1 showed 0.52 and 0.64 mm of movement with the fully fixed and relaxed models. Versus ExFix2 with 2.20 and 2.74 mm of movement respectively (Fig. 4A and b).

Stress Pattern

The stress contour plots of the equivalent von Mises stresses for each fixator component are shown in Figure 5. In all components of the fixator ExFix1 experienced lower overall stress than ExFix2, in both axial and torsional loading. For all FE analysis maximum stress occurred at the pin-Tufnol interface. In axial loading of both fixators, stress peaks in the pin closest to the point of loading was seen, whilst in torsion, maximum stress occurred in the pins either side of the fracture gap.

DISCUSSION

This study compared the mechanical characteristics of two commonly used external fixators in small animal fracture models. We used our in vitro findings to validate a series of FE models based on axial and torsional stiffness data. Between the two fixators, we found significant differences in stiffness in both the axial and rotational planes, with ExFix1 markedly more rigid in both planes. Throughout the study we maintained a constant offset, pin material and pin diameter, thus allowing the fixator design and crossbar material (Ti alloy/carbon fibre vs. PEEK) to be the dominating factors on overall stiffness. Previous studies have determined that pin size and material are the greatest determinants of fixator stiffness and interfragmentary fracture movement, also demonstrating the importance of offset and pin number,[10,23,24] our data also suggests the significant impact that the fixator material properties and bar configuration have on the overall stiffness.

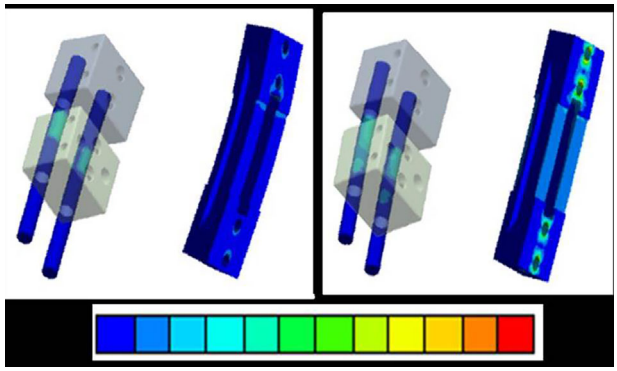

Figure 5. Equivalent von-Mises stress contour plots on the crossbars of both fixator models.

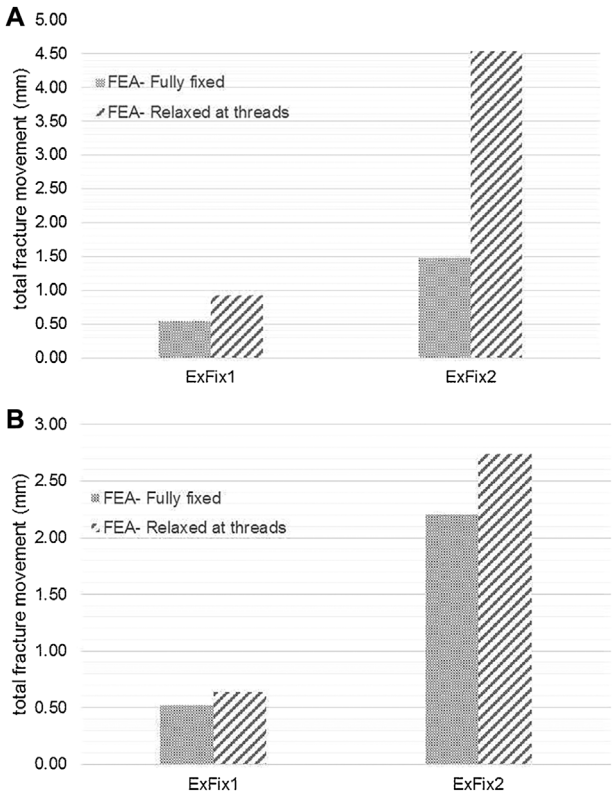

Figure 4. (A and B) Demonstrating total fracture movement as found in silico under compression (A) and torsion (B).

In vitro axial stiffness of both ExFix constructs were significantly less than those found with locked nailing techniques.[25] ExFix1 was a third as stiff, and ExFix2 just over half as stiff as reported nailing data.[25] Conversely rotational stiffness was greater for the external fixators than locked intramedullary nails, and indeed was greater than physiological numbers from intact bone (torsional stiffness 23 Nmm/°). This greater stiffness in rotation, if related in vivo, will lead to reduced interfragmentary movement in shear and as such will impact bone formation.

Our data suggests the FE model could predict the relative differences between the two external fixators. However, the FE models consistently predicted larger stiffness' then those found in vitro, this difference was considerably larger in the "fixed" model that did not account for any micro-motion at the pin-Tufnol or the pin-fixator interfaces. When relaxing the interfaces, the comparative ratios fell notably and were closer to the experimental in vitro data (see Fig. 2). Again highlighting the fundamental role of micromotion at the interfaces in both the in silico and in vitro tests.[17]

A relatively large body of work has evaluated the role of FE modeling in clinical fracture fixation scenarios. For example, Ramlee et al.[26] reviewed two external fixators with an FE model and their effects on subtalar dislocation reduction, similarly, Varga et al.[27] reviewed the use of compression screws in scaphoid

fracture fixation and the effects these have on interfragmentary forces and again fracture reduction. Both of these studies among others (e.g., Ref.[3,28]) have validated FE models and underlined their utility in clinical fracture management. Our study uses the modeling technique in the preclinical setting; importantly allowing an understanding of the fracture mechanics without the need for lengthy in vivo experiments. Moreover, the validation of our relaxed FE model, that adjusts for interface micro motion, results in the creation of a tool that can allow the design and manipulation of a fixator to best suit different experimental parameters.

The difference in stiffness has a predictable effect on movement at the fracture gap, which has important implications on fracture healing. Interfragmentary motion of between 0.2–1 mm perpendicular to a diaphyseal fracture has been found to promote union; however, excessive axial and shear motion will result in delayed healing.[1–3] Under axial conditions ExFix2 experiences significant motion where bony fragments come into contact. ExFix1, however, restricts vertical motion under axial loading to less than 1 mm, within the desired envelope. Under torsion, this increases to a value equating to a rotation of up to 17 degrees. ExFix1 limits rotation to less than half this amount at the same levels of loading. Under axial loading, translation and rotation at the fracture gap in ExFix1 is also negligible. Additionally, our findings are particularly relevant when investigating biological and pharmacological interventions where variability in stress across the gap will directly influence the efficacy of these factors.[29–31]

The specific pin where the maximum stress occurs changes between loading conditions. In axial loading, maximum stress is located on the most proximal pin in both ExFix1 and 2 whereas under torsion, maximum stress occurred in the pin nearest the proximal end of the fracture. These changes are likely to be a function of the constraint of the Tufnol bone creating higher stresses in the pins adjacent to the fracture site.

While the FE model could not exactly represent the in vitro assembly boundary conditions, the two conditions that were investigated can accurately predict upper and lower limits for in vitro results. Ultimately, we demonstrated considerable differences in the overall stiffness between the two fixators, which should be considered when comparing experimental in vivo data on fracture healing. Given a consistent fracture gap fractures stabilized using ExFix2 are more likely to heal though endochondral ossification or go onto a delayed or non-union compared to ExFix1. The in silico model where the threads are not fully bonded, predicted the comparative stiffness between the two fixators, as evidenced by the similar ratios. This data suggests that a computational protocol that includes the micro-motion present at the pin-bone interface, results in a reproducible model of experimental conditions. Further in vivo and computational work is required to demonstrate the effect of gap distance and fixator stiffness on the rate, type, and quality of ossification and healing.

AUTHORS' CONTRIBUTIONS

LOC, manuscript preparation, data collection, experimental design. JK experimental design, data collection. GB, experimental design, manuscript preparation. MC/CP/TB, experimental design and data analysis. RM, computational modeling and manuscript preparation. MM, experimental design, data analysis, manuscript preparation. All authors have read and approved the final submitted manuscript.

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