External Fixation for Treating Tibial Shaft Fractures Using a Triangular Two-Planar Frame: A Computational and Biomechanical Study

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Abstract

Background: Construct stability is a necessary characteristic of external fixators. Many commonly used fixators are constructed as symmetric one-plane frames. We postulate that asymmetric two-plane triangular constructs provide enhanced stability with simplicity and freedom in pin placement. We hypothesized that results of finite element analysis would determine optimal geometric configuration, and findings of mechanical testing would confirm the improved stability of two-plane triangular constructs.

Methods: Finite element modeling was used to analyze configurations for 16 triangular designs compared to a single-rod (SR) uniplanar frame. Variables included pin axial angulation (0°, 22.5°, 45°, and 90°), connectivity of the rod-to-pin couplers, and intrafragmentary pin spacing (75mm or 100mm). Construct stiffness and interfragmentary displacement were analyzed for model selection. In a subsequent experimental test, nine synthetic composite tibiae were displaced to a maximum of 4 mm, comparing compressive load and axial stiffness of triangular construct with those of SR and pin-clamp (PC) uniplanar frames.

Results: Computational modeling showed that greater pin spacing results in increased stiffness ($P < 0.001$), but increased interfragmentary displacement ($P = 0.01$). 22.5° and 45° constructs were significantly stiffer than 0° constructs ($P = 0.03$ and $P = 0.01$, respectively). Displacement was significantly less in 22.5°, 45°, and 90° than 0° constructs ($P = 0.01$). Experimentally, the 22.5° triangular multiplanar constructs were significantly stiffer with higher compressive loads than uniplanar constructs ($P < 0.001$).

Conclusions: A two-plane triangular frame may be a more stable construct than the two symmetric uniplanar constructs tested. This configuration allows for greater adjustability than SR constructs, requiring no specialized devices as do PC constructs, while allowing simplicity and freedom of pin placement.

Introduction

External fixators are used for temporary and definitive management of fractures. Originally developed for definitive fixation, the use of this method waned in the 1980s because internal fixation became popular.[1] In the 1990s, however, external fixators regained prominence in treating injuries associated with multiple traumas, frontlines of battle, third-world settings, and fractures with soft-tissue injury and subsequent high risk of infection (used as a temporizing measure).[2,3]

Compared to internal fixation, use of external fixators involves considerably less dissection of soft tissue and disruption of blood supply, which helps treat acute traumatic injuries in which extensive soft-tissue damage may limit or preclude the use of internal fixation devices.[3,4] Tibia fractures are a common indication for treatment with external fixation, including open tibia shaft fractures, distal tibia plafond fractures, and complex proximal tibia fractures with soft-tissue injury. In these regions subject to high levels of anatomical loading, frame stability is essential to maintain reduction and limb alignment.

External fixation provides relative stability, in which endochondral healing can occur in early fracture healing.[5,6] Basic principles have been clearly defined and supported by numerous biomechanical studies, which support five common techniques for increasing frame stability:
1) increase the distance between pins within a fragment;
2) increase the number of pins within each fragment;
3) decrease the distance between the bone and frame;
4) add additional rods, tubes, and rings; and
5) use large diameter pins.[3,4] Some of these basic techniques have been addressed by manufacturers in developing external-fixation devices used today. Because fracture types can vary, the use of a single standardized technique may not be optimal for all surgical treatments.[7] A thorough understanding of basic mechanical principles and their implementation using universal and basic components of external fixation can help optimize construct design.

One of the most common frame designs in use is a simple, one-plane frame with parallel pins and a single longitudinal connecting rod or variations of that basic geometry (ie, use of specialized pin clamps).[8] We propose that the use of a truss design with two-plane triangular frame can increase structural stability, increase frame adjustability, and allow for controlled, interfragmentary motion while limiting the need for costly, specialized and bulky external fixation components. Even when applied to the short-term temporizing of fractures to stage future removal and placement of internal fixators, an improved stability increases the likelihood that the initial reduction will be maintained and patient comfort will be maximized.[5,6] The first aim of the current study was to developed a low-profile, triangular multiplanar external fixator configuration for treating tibial shaft fractures. The second aim was to experimentally compare the stiffness and compressive load (as measurements of construct stability) of the optimized multiplanar design to two commonly-used external fixators: the single rod (SR) uniplanar and pin-clamp (PC) uniplanar constructs.

Methods

Computational Modeling and Validation (Aim 1)

Triangular multiplanar construct development. Using computational modeling and analysis techniques, we investigated a novel, mechanically stable configuration of external fixation components for treating tibia shaft fractures. With careful measurement of each component used, we modeled Hoffmann II MRI external-fixation components (Stryker, Kalamazoo, MI) using SolidWorks 3D modeling software (Dassault Systemes, Waltham, MA). A design of experiments method was used to analyze possible configurations for the fixation components, with the general structure derived from the concept of a truss—one or more triangular units—designed to be compact yet structurally stable. The design emphasizes important biomechanical principles in external fixation and provides controlled interfragmentary motion for formation of new bone.[9,10] The optimal configuration would be more compact and inexpensive than uniplanar designs but provide increased structural stability and adjustability in all degrees of freedom for correction of initial malreductions, which is capable with pin-clamp and other unconstrained multiplanar constructs.[11,12]

There were three model variables: second and third (closest to fracture) pin axial angulation at 0°, 22.5°, 45°, and 90° from the most proximal (first) and distal (fourth) pins; connectivity of the rod-to-pin couplers of the first and fourth pins in outer or inner configuration (ie, away from or near central fracture, respectively); and pin spacing within each fragment (100 mm or 75 mm between innermost and outermost pins; Figure 1). The third variation is addressed in external fixation basic principles and is used for model validation.[4] Distance between frame and shaft (20 mm) and between innermost pins (ie, second and third pins; 50 mm) was minimized and kept constant.[4,12]

The 16 possible model configurations (treatments) are listed in Table 1. These configurations were computationally fixed to a 25.4-mm (1-inch) diameter solid cylindrical rod designed to mimic basic tibia shaft geometry. Each rod had a segment removed from the midsection to simulate a mid-shaft tibial fracture, with 10 mm of comminution. Construct stiffness and vertical interfragmentary displacement were analyzed for model selection. An ideal configuration would allow for high bone and implant construct stiffness and minimal interfragmentary displacement.

Computational modeling parameters and boundary conditions. ANSYS Workbench finite element software was used to analyze the models (Canonsburg, PA). Material properties were assigned to the external fixation components matching materials defined in the Osteosynthesis Hoffmann II MRI External Fixation Systems guide (Stryker, Kalamazoo, MI; stainless steel pins = 193 GPa, aluminum alloy couplers = 71 GPa, carbon fiber rods = 175 GPa). Material modulus assigned to the solid cylindrical rods matched Poplar wood used for experimental validation (10.9 GPa). Boundary conditions simulating a simplified model of single leg stance were defined. Bonded contact conditions were defined at all component interfaces, assuming that there is no loosening of components during the simulated loading condition. The inferior aspect of the distal shaft was fully fixed to simulate a worst-case scenario of no ankle motion to limit variability in the model. A displacement-controlled stepped loading protocol was applied to the superior aspect of the proximal shaft (maximum displacement, 4 mm).

Model comparison with single-rod uniplanar construct. A 3D solid model of a commonly used configuration, known as a single-rod uniplanar (SR) construct, was developed for comparison with the triangular multiplanar designs. Placement of the pins followed a technique outlined in the AO Principles of Fracture Management.[4] A 5-mm stainless steel pin was placed into each main fragment at the proximal and distal ends, exactly 125 mm from the osteotomy site. The two pins were connected by a single carbon fiber rod using the metal rod-to-pin connectors. An additional pin was placed on the proximal and distal fragments, 20 mm from the osteotomy site, parallel with the first pins, and subsequently connected to the rod with rod-to-pin connectors. Outcome measures from the finite element model were construct stiffness determined from load and displacement data and vertical interfragmentary displacement.

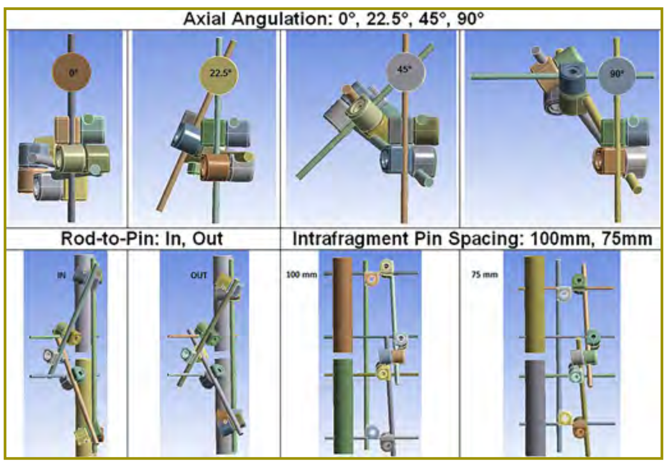

Figure 1. (Top) Axial view of triangular constructs, showing angulation of second and third pins at 0°, 22.5°, 45°, and 90°. (Bottom, Left) Anteroposterior view of constructs, showing inner or outer rod-to-pin clamp placement. (Bottom, Right) Medial-lateral view, showing intrafragment pin spacing at 100 mm or 75 mm.

Table 1. Full factorial design of experiments to observe the combined effects of varying outer pin (first and fourth) rod-to-pin coupler placement, pin spacing within fragments, and inner pin (second and forth) axial angulation[a,b]

Rod-to-pin placement	Pin spacing – fragment, mm	Axial angulation, degrees			
		0	22.5	45	90
In	75	1	2	3	4
	100	5	6	7	8
Out	75	9	10	11	12
	100	13	14	15	16

[a] Sixteen treatments were available for analysis.
[b] Results of this experiment were used to select an ideal configuration for experimental testing of the triangular external fixation frame design.
[c] Interfragmentary spacing (10 mm), distance between frame and shaft (20 mm), and distance between innermost pins (50 mm) was kept constant.

Experimental Testing (Aim 2)

We experimentally compared the selected triangular configuration to two commonly used external fixator constructs—SR uniplanar and PC uniplanar—in a synthetic bone model. A power analysis was completed utilizing 5 N/mm as the clinically significant difference in stiffness, on the basis of results from preliminary testing of six triangular configurations using wood as the simulated bone material. A minimum sample size of 3 specimens per treatment group was adequate to detect this difference ($\alpha = 0.05$ and $\beta = 0.20$). Nine synthetic, fourth-generation composite tibiae (Pacific Research Laboratories, Vashon, WA) were used to compare each of the three constructs using a custom-designed test fixture.

External fixation construct assembly. All half-pins were inserted with an anteromedial to posterolateral trajectory, with the starting point just medial to the tibial crest, by a trained orthopaedic surgeon. A 10-mm osteotomy was created mid-shaft. A jig to guide reproducible placement of half-pins and cutting of the osteotomy was created by casting of the synthetic tibia.

The SR uniplanar construct placement follows the method in the previous section. For the PC uniplanar construct, two pins were placed in each main fragment similar to the SR uniplanar method. The proximal shaft pins were connected by a 10-hole pin clamp at the most proximal and distal clamp holes. The distal-shaft pins were connected in the same manner. We placed 30° aluminum angled posts in the two distal holes of the proximal clamp and in the two proximal holes of the distal clamp. The proximal- and distal-angled posts were connected by single carbon fiber rods using aluminum rod-to-rod connectors.

For the optimized triangular fixation, a 5-mm stainless steel pin was placed into each main fragment at the proximal and distal metaphyses, at 125 mm from the osteotomy site. An additional pin was placed on the proximal and distal fragments, at 25 mm from the osteotomy site, with an axial angle of 22.5° from the first pins. Aim I computational models produced a range of values that would be acceptable for this technique (as described in Results section). The minimum angle of 22.5° was chosen for the experimental portion of this study because it produced the most compact structure with minimal potential for impingement of soft tissue. The most proximal and distal pins were connected by a single carbon fiber rod using the aluminum rod-to-pin connectors. The proximal and distal pins in the proximal fragment were connected by a short carbon fiber rod using aluminum rod-to-pin connectors. The same technique was used to connect the two pins in the distal fragment. A final rod-to-rod connector connected the proximal and distal short carbon fiber rods near the fracture site. SR uniplanar, PC uniplanar, and triangular two-planar constructs are shown in Figure 2.

Testing protocol. A custom-designed fixture was developed for experimental testing. A Mini-Bionix servohydraulic actuation system (MTS Systems, Eden Prairie, MN) was used to apply external loads simulating a single-leg stance loading condition. To accurately recreate an anatomical loading condition created by the settling and accommodation of the joints around a loaded tibia, we avoided rigid fixation of either the proximal or distal ends of the tested tibiae.[13] Instead, this physiological accommodation was simulated by using a total knee arthroplasty component proximally and a universal joint distally.

The femoral component of a total knee prosthesis was attached to the actuator of the testing machine. The tibial component of the total knee prosthesis was attached to the proximal tibia using a spacer box and acrylic casting material, allowing articulation of the tibial and femoral total knee components. An automotive driveshaft universal joint was used to simulate the ankle and subtalar joints distally (Figure 2). A displacement-control protocol ramped at 1 mm/s (maximum displacement, 4 mm) was used to compare the compressive load at 4 mm and axial construct stiffness as measures of relative construct stability. Stiffness was defined as the slope of the most linear region of the load-displacement curve. A preload of 50mN was used for all tests.

Statistical Analysis

Main effects and interactions of rod-to-pin coupler placement, pin spacing, and axial angulation from computational modeling of triangular constructs were analyzed using Minitab 16 (Minitab, State College, PA). Experimental data from all specimens were tabulated, and statistical analysis was performed in conjunction with biostatisticians. Ultimate load and stiffness between fixation constructs were compared using a one-way analysis of variance (ANOVA), with use of the Fisher least significant difference method to investigate relationships between subgroups.

Figure 2. External fixation constructs tested in experimental study (aim 2). (Left) Single-rod uniplanar. (Middle) Pin-clamp uniplanar. (Right) Triangular two-planar. A total-knee prosthesis was used to simulate tibial-femoral articulation. A universal joint was used to simulate the ankle and subtalar joints distally.

Results

Triangular Multiplanar Construct Selection

Sixteen possible model configurations were analyzed using simulated axial loads; results are listed in Table 2. The most significant factor affecting construct stiffness was pin spacing, with greater pin spacing resulting in increased construct stiffness (100-mm spacing = 126.0 N/mm [SD, 5.6 N/mm]; 75-mm spacing = 99.5 N/mm [SD, 9.6 N/mm]; $P < 0.001$). No significant difference in stiffness was found between constructs with inner or outer rod-to-pin coupler placement. When comparing the effects of axial angulation, stiffness was significantly higher in 22.5° and 45° than 0° constructs ($P = 0.03$ and $P = 0.01$, respectively). Main effects and interaction plots for stiffness are shown in Figure 3.

Table 2. Results of the 16 possible model configurations analyzed using finite element modeling

Treatment	Factors included[a]	Vertical interfragmentary displacement, mm[b]	Stiffness, N/mm[c]
5	0°;out;100mm	2.9	124.0
13	0°;in;100mm	2.9	123.1
1	0°;out;75mm	2.5	87.5
9	0°;in;75mm	2.7	94.2
6	22.5°;out;100mm	2.4	126.4
14	22.5°;in;100mm	2.4	128.8
2	22.5°;out;75mm	2.2	96.7
10	22.5°;in;75mm	2.3	98.0
7	45°;out;100mm	2.2	129.6
15	45°;in;100mm	2.3	130.7
3	45°;out;75mm	2.2	98.4
11	45°;in;75mm	2.1	98.5
8	90°;out;100mm	2.1	131.3
16	90°;in;100mm	2.5	114.3
4	90°;out;75mm	2.1	100.7
12	90°;in;75mm	2.1	122.0

[a] "Out" and "in" refer to rod-to-pin clamp placement in relation to osteotomy site.
[b] Axial angulation and pin spacing had the most significant effects on interfragmentary displacement. In-line pins (0°) resulted in increased interfragmentary displacement.
[c] The most significant factor affecting construct stiffness was intrafragmentary pin spacing with greater pin spacing resulting in increased construct stiffness.

Axial angulation and pin spacing had the most significant effects on interfragmentary displacement. Displacement was significantly less in constructs with 75-mm pin spacing ($P = 0.01$). Displacement was significantly less in 22.5°, 45°, and 90° than 0° constructs ($P = 0.01$ for all). Displacement was also significantly less in 45° than 22.5° constructs ($P = 0.02$). No significant difference in displacement was found between constructs with inner or outer rod-to-pin coupler placement. Main effects and interaction plots for interfragmentary displacement are shown in Figure 4.

Model Comparison with Single-Rod Uniplanar Construct

The SR uniplanar computational model stiffness was 84.4 N/mm and the interfragmentary displacement was 2.6 mm. The SR uniplanar construct had a displacement in the range of the triangular multiplanar design (range, 2.1-2.9 mm). The stiffness of all configurations of the triangular construct exceeded that of the SR uniplanar design (87.5-131.3 N/mm). Figure 5 shows finite element displacement contour plots for the SR uniplanar and the 22.5° triangular uniplanar construct.

Experimental Results

Results from the computational analyses showed that the 22.5° and 45° constructs, with 100-mm pin spacing and inner or outer rod-to-pin clamp placement, met optimal requirements for clinical use of an external fixation device—high stiffness and controlled interfragmentary displacement. The 22.5° configuration with 100-mm pin spacing and outer clamp placement was selected for the experimental study because high construct stiffness is important in early bone healing.[6,14,15] Additionally, this configuration involves the most compact design next to the single plane constructs.

In experimental tests, the 22.5° triangular multiplanar constructs (65.3 N/mm [SD, 5.0 N/mm]) were significantly stiffer than SR uniplanar (37.3 N/mm [SD, 1.6 N/mm]) and PC uniplanar (26.1 N/mm [SD, 1.6 N/mm]) constructs ($P < 0.001$). Compressive load to achieve 4-mm displacement was significantly higher for triangular multiplanar constructs (271.8 N [SD, 19.4 N]) than SR uniplanar (155.4 N [SD, 6.9 N]) and PC uniplanar (109.4 N [SD, 6.4 N]) constructs ($P < 0.001$).

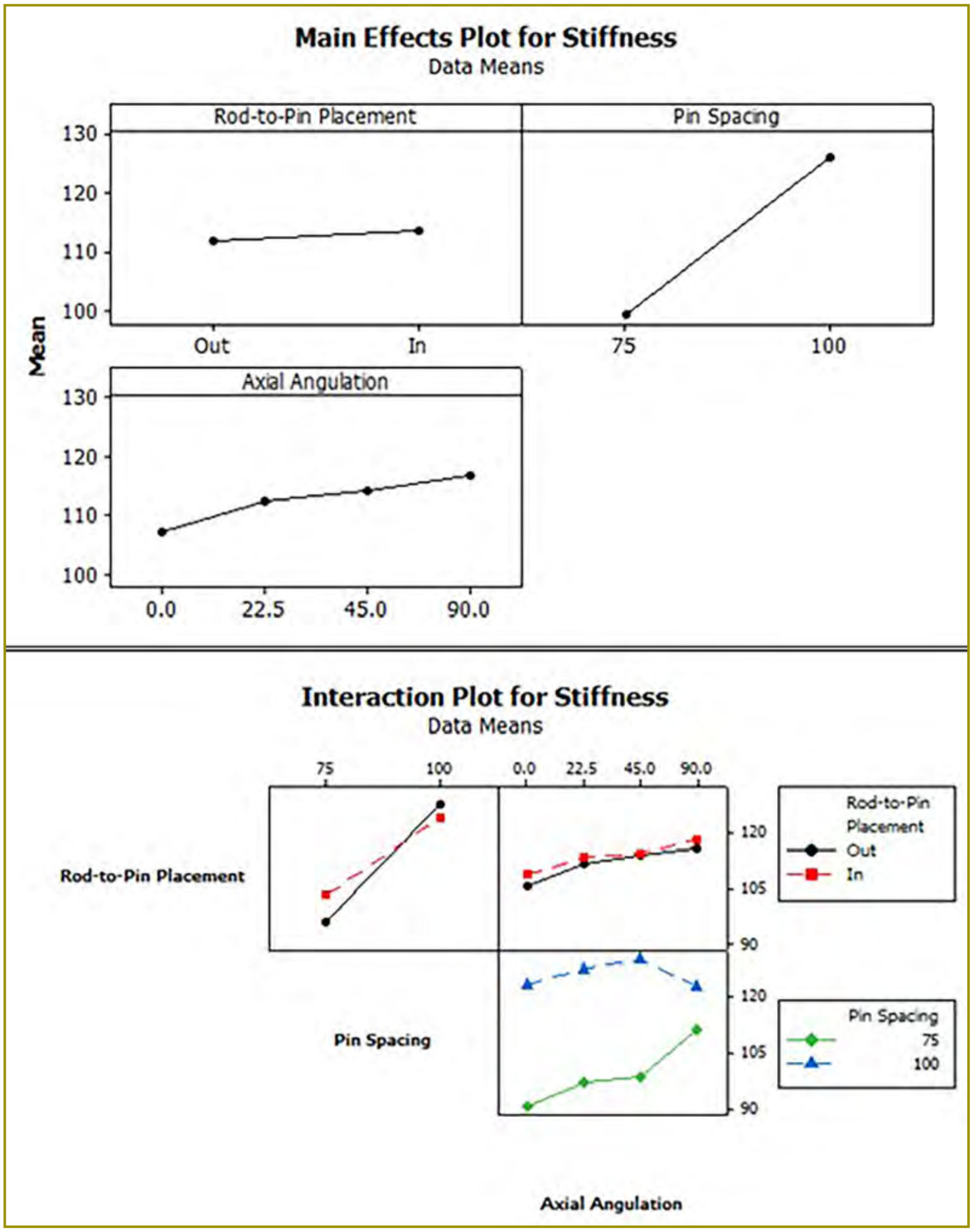

Figure 3. Mean effects (Top) and interactions (Bottom) plots for stiffness. Input variables are rod-to-pin placement, pin spacing, and axial angulation. Pin spacing was the most significant factor affecting stiffness. Greater pin spacing resulted in increased construct stiffness.

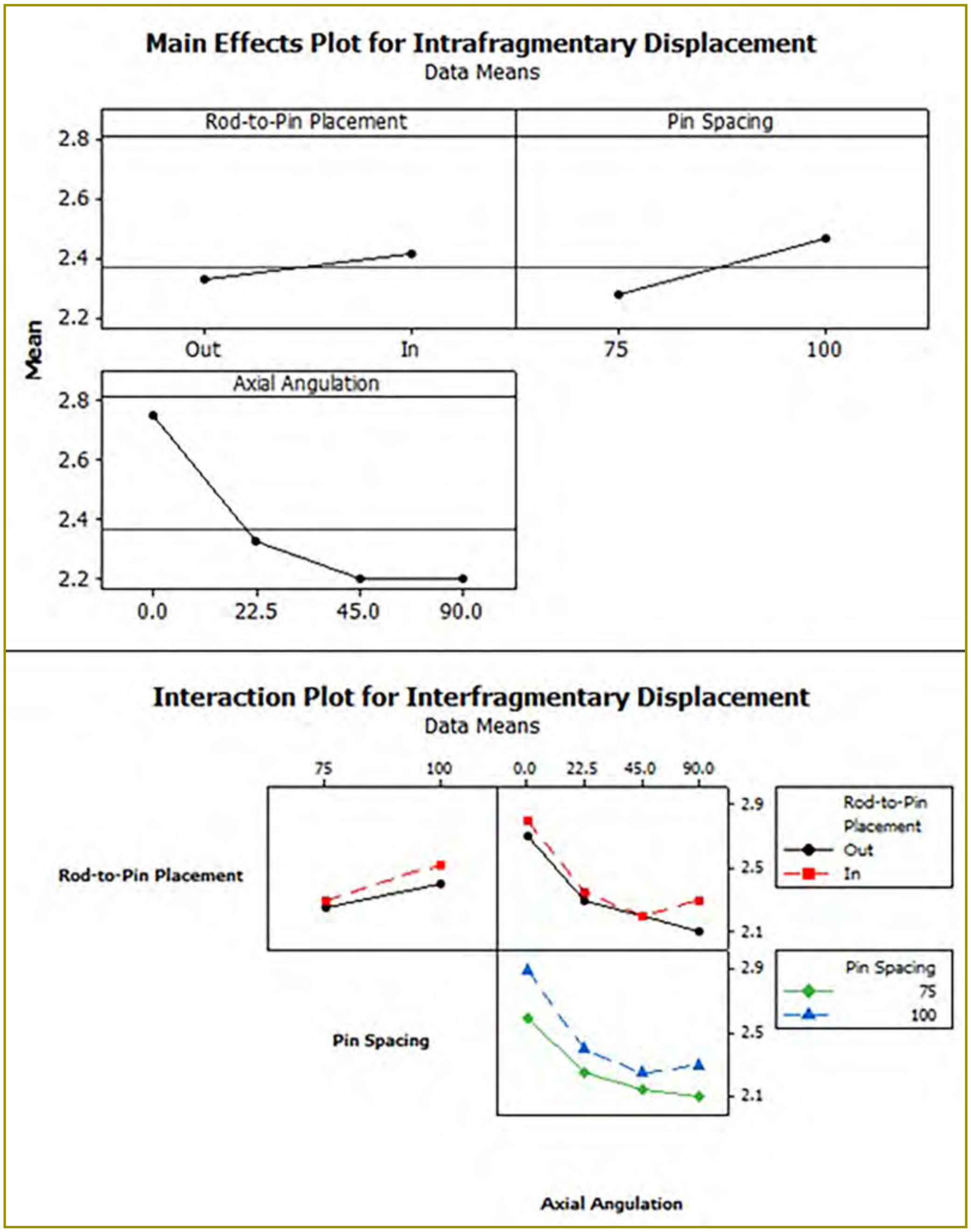

Figure 4. Main effects (Top) and interactions (Bottom) plots for interfragmentary displacement. Axial angulation and pin spacing had the most significant effects on displacement. Displacement is significantly less in constructs with 75 mm pin spacing and angulations of 22.5°, 45°, and 90°.

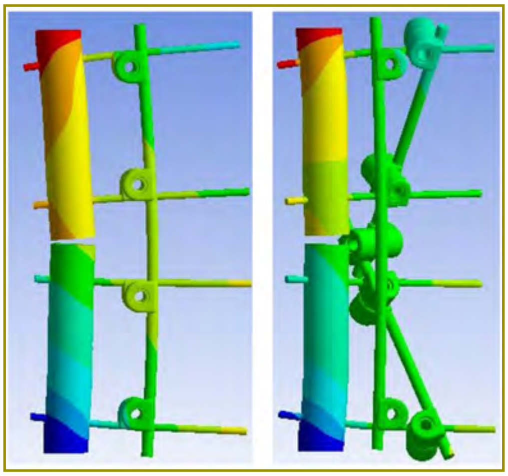

Figure 5. Displacement contour plots of single-rod uniplanar (Left) and 22.5° triangular multiplanar (Right) constructs from finite element modeling. Under the same applied conditions, the single-rod uniplanar has greater interfragmentary motion.

Discussion

In aim 1, we analyzed 16 computational models of external fixation configurations developed to utilize the inherent benefits of the mechanical-engineering truss principle. The configurations were created using basic principles outlined by the AO foundation for increasing the structural stability of an external fixation device.[4] The principle of increasing the distance between pins within a fragment was used for model validation.Greater intrafragmentary pin spacing ($P < 0.001$) and 22.5° or 45° inner pin axial angulation ($P = 0.03$ and $P = 0.01$, respectively) significantly increased the structural stiffness of the constructs.

Our finding supports the pin-spacing principle affirmed by the AO Foundation and others, stating that increased pin spacing within a fragment increases stiffness of the construct.[4,16] Our results confirm that our testing method was sufficiently sensitive to detect a clinically important change in construct stability. Additionally, we found that interfragmentary displacement was significantly reduced with closer intrafragmentary pin spacing ($P = 0.01$) and further reduced with 45° than 22.5° constructs ($P = 0.02$).

In the current study, the 22.5° construct (with 100-mm intrafragmentary spacing and outer rod-to-pin clamp placement) was used for experimental comparison with the SR and PC uniplanar constructs because it maintained a high stiffness and was compact similar to the SR uniplanar fixation. We found 22.5° multiplanar constructs to be significantly stiffer and had significantly higher ultimate loads at 4-mm displacement compared with that of SR and PC uniplanar constructs ($P < 0.001$).

The triangular two-plane construct presented in this study combines advantages of SR and PC frame designs while avoiding their negatives. A main advantage includes high initial construct stiffness, with capability to easily increase or decrease stiffness by addition, removal, or adjustability of components even after the construct is fully built.[6] These characteristics are summarized in Table 3. A triangular external fixation configuration was proposed early by Fernández[17] to increase the torsional stiffness of a bilateral fixator. In his study, the triangular fixator was more than three times stiffer in torsion than unilateral, uniplanar constructs. Notably, the triangular construct was unilateral and biplanar, which would not transfix the lateral compartment. The triangular truss principle has been applied clinically at our institution for temporary and definitive treatment of tibial and humeral fractures. This technique has been employed when commonly used external fixation options have failed. Figure 6 outlines examples of the triangular principle applied in practice.

Limitations exist in the current study. Variables in the computational model were limited to three factors available to surgeons during placement (axial pin angulation, pin spacing, and clamp). Use of a multivariate probabilistic analysis may help determine definitively whether pin spacing or axial angulation (other than the points measured) affected the results, given the wide spectrum and variability from constraints of individual patient and injury characteristics. In the experimental study, the use of synthetic specimens is a limitation. Use of fourth-generation composite tibias eliminated variability attributed to bone quality in cadaveric specimens, which greatly reduced the number of specimens neeed to achieve significance but did not allow us to examine how variations in bone quality may be affected by each construct type. Additionally, we compared the triangular construct to two commonly used uniplanar designs. To fully test its performance for clinical use, it would be necessary to compare this construct to commonly used hybrid and circular-ring fixators. However, in an acute trauma and temporizing application, hybrid and ring fixators are rarely used. With a biomechanical study, we can only theorize clinically relevant advantages of the triangular fixator. A controlled clinical study would allow comparison of surgical time for placement, need for guides for precise placement of half-pins, and ease of implementation.

In the current study, use of a two-plane triangular external fixation frame yielded a construct more structurally stable than the two symmetric SR and PC uniplanar comparison constructs, while also being more adjustable than single-rod constructs. The proposed two-plane triangular external fixation does not require the specialized devices necessary for PC constructs and allows simplicity and freedom of pin placement that can be helpful in settings where external fixators are important.

Table 3. Advantages and disadvantages of the triangular two-planar, single-rod uniplanar, and pin-clamp uniplanar constructs[a]

Advantage (+)	Construct			Disadvantage (-)	Construct		
	Single-Rod	Pin-Clamp	Triangular		Single-rod	Pin-clamp	Triangular
Uses simple, readily available components	+		+	Loading causes bending deformation and asymmetric stimulation of cortical new bone formation	-	-	
High initial construct stiffness			+	Initial pin placement determines many aspects of final reduction	-		
Easily increase or decrease stiffness by addition or removal of components	+		+	Difficult to add pins for additional stability when used as definitive/long-term treatment		-	
Adjustable in all degrees of freedom (angular, length, rotation) even after construct fully built		+	+	Loss of stiffness with purposeful build-down as healing progresses		-	
Compact and low-profile	+		+	Constrained by placement of pins			
Forgiving pin placement/ pins may be placed with focus on safe-zones			+	Limited by rod trajectory	-		
				Limited by pin-clamp design/length		-	

[a] The triangular two-plane construct combines advantages of single-rod and pin-clamp frame designs while avoiding their negatives.

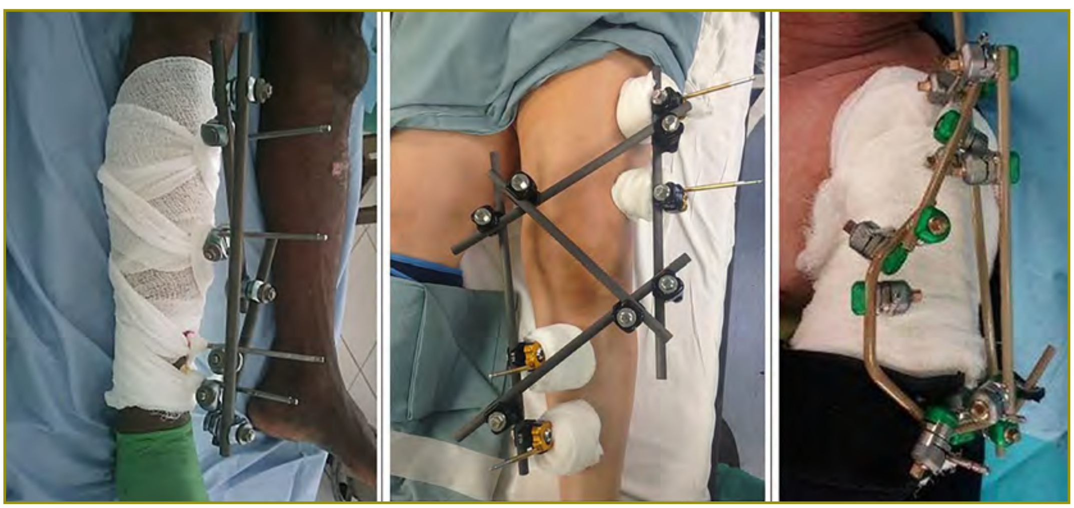

Figure 6. Clinical application of principles verified in this study. (Left) Triangular tibial external fixator investigated in this study. (Middle) Knee-spanning external fixator, showing safe femoral and tibial pin-placement. (Right) Humerus-shaft external fixator, successfully used in definitive treatment after pullout failure of a pin-clamp construct in this patient with fused shoulders.

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Conflict of Interest

The authors report no conflicts of interest.

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