Correlation of Shear to Compression for Progressive Fracture Obliquity

David W. Lowenberg MD, Sean Nork MD,
Frederick M. Abruzzo MD

Published online: 27 September 2008
© The Association of Bone and Joint Surgeons 2008

Abstract The accompanying shear force at the point of bone opposition is an important factor inherent to tibial fracture stability during axial loading. We determined at which angle of fracture obliquity shearing becomes a dominant force after stabilization with circular external fixation, and how modifications to the external fixator can reduce this effect. We constructed tibial fracture models with a successively increasing fracture angle obliquely (from 0° to 60°) to determine the stability in the classic Ilizarov frame and subsequent frame modifications during axial loading (maximum, 1000 N). Stability was determined by measuring the fracture line displacement for each fracture obliquity model after an applied axial load. Fracture line displacement was recorded as coordinate component changes as measured by an ultrasonic digitizer. We defined construct stability as less than 2 mm of fracture line migration with loading. More than 3500 data points were collected for this study. The classic Ilizarov construct successfully stabilized fractures with up to 30° of fracture obliquity, after which divergent instability occurs. The addition of proximal and distal perpendicular half-pins provides little benefit. Arced wires provided stability up to 40° fracture obliquity. A formal steerage pin construct

provided stability for all fracture models (up to 60° of fracture obliquity) with all applied loads (up to 1000-N axial load).

Introduction

The Ilizarov apparatus is widely accepted as the prototype in circular fixator design. The basis of the system rests on its ability to provide multiplanar fixation using wires under tension. The mechanical characteristics of external fixators may influence the biologic environment at the fracture site and ultimately contribute to fracture healing. Thus, knowledge of the mechanical properties of a fixator is essential in clinical practice.

Circular external fixation offers considerably stronger fixation than does its unilateral counterpart. Duda et al. [5] compared the Ilizarov fixator with unilateral external fixators in a tibial model. For similar applied loads, there was a fourfold decrease in varus/valgus angulation and a sevenfold decrease in anteroposterior angulation with the circular fixator as compared with the unilateral fixator. This is attributable in part to the cantilever phenomenon of unilateral fixators. However, these authors demonstrated a 1.75-fold increase in axial pistoning (axial micromotion) with the circular wire fixator as compared with the unilateral fixator. This increased axial micromotion, with relatively high axial displacement at low axial loads and progressively lower axial displacement at high axial loads, distinguish the behavior of the Ilizarov fine wire external fixator from all other fixation methods. The combination of increased axial micromotion and decreased sagittal and coronal plane angulation with loading is hypothesized to contribute to the clinical success of the Ilizarov construct in clinical practice. Gardner et al. [6, 7], in a biomechanical

One or more of the authors (DWL) have received funding from the Koret Foundation. No author received personal funding. All funding was for materials and testing equipment.

D. W. Lowenberg (✉), F. M. Abruzzo
Department of Orthopaedic Surgery, California Pacific Medical
Center, San Francisco, 2100 Webster Street #117, San Francisco,
CA 94115, USA
e-mail: dwlowenberg@yahoo.com

S. Nork
Department of Orthopaedic Surgery, Harborview Medical
Center, University of Washington, Seattle, WA, USA

study comparing tibial fracture stabilization with a statically locked unilateral external fixator compared with the same fixator in a dynamic mode, found enhanced clinical and mechanical stability with a shortened healing time in the dynamic mode group. They credited this to the axial micromotion [6, 7]. This was confirmed in an ovine tibial model where Draper et al. [4] compared conventional stabilization and unilateral external fixation. In the axial micromotion group, there was a fourfold increase in corticomedullary blood flow and increased periosteal cross-sectional area at 2 weeks as compared with the conventional stabilization group.

The preponderance of articles confirm that shear across the fracture is detrimental to healing with only one publication suggesting the opposite [14]. However, in addition to the stability provided by the mechanical fixator, the fracture configuration and obliquity contribute to the overall construct stability.

We therefore designed this study to quantify the relationship between fracture obliquity and shear during physiological loading in a tibial fracture model stabilized with circular external fixation. We also sought to quantify the influence of different Ilizarov external fixator frame modifications on the overall construct stability and the ability of these modifications to neutralize the observed fracture site shear.

Materials and Methods

A biomechanical model was designed to evaluate the stability of various modifications to a standard Ilizarov fixator used to stabilize a midshaft tibial fracture with increasing fracture obliquity ranging from purely transverse to 60° of obliquity. Fixation stability was quantified by measuring the fracture line migration after an axial load was applied. Axial load was increased by 200 N increments up to a maximum of 1000 N, simulating physiological loads in adult males with ambulation. Migration was determined by measuring a series of focal component coordinate displacements (FCCD) using an ultrasonic digitizer.

We used a composite synthetic tibia bone model (Sawbones Inc, model no. 3302, Pacific Regional Laboratories, Vashon, WA), to maintain consistency and eliminate the variability of cadaveric bones. After placing the bone models in their corresponding fixator apparatus, an oblique transection was created with an oscillating saw to simulate a uniplanar fracture. All of the fracture models were constructed in a similar fashion varying only by coronal fracture angle obliquity as measured from the horizontal plane. Six groups were studied with coronal fracture obliquities of 0°, 15°, 30°, 40°, 50°, and 60° and titled groups A through F, respectively. Osteotomies were

created using a saw blade of identical thickness. The fracture obliquities were created using a pre-templated cardboard cutout.

Axial loading was generated by a floor-mounted Bionics Servo-Hydraulic Materials Test System (MTS), Model 858 (Bionix Development Corporation, Toledo, Ohio). This tabletop system can be configured for characterizing the static and fatigue properties of low-strength materials. The load cell was calibrated to eliminate the contribution of gravitational force from the bone-fixator composite itself. In this way, any applied force represented total axial load. The load was applied gradually to avoid induction of an accelerated force (burst load). The data was entered into a computer to be analyzed by a Microsoft Excel spreadsheet (Microsoft, Redmond, WA).

A standard four-ring, eight wire Ilizarov fixator (Smith & Nephew, Memphis, TN) was constructed. The frame was balanced to the tibia with transverse lateral to medial olive wires (wire diameter, 1.8 mm) at the proximal and distal tibial metaphysis at the proximal and distal ring, respectively. Further fixation was achieved with proximal and distal tibiofibular smooth wires at these two rings. The second and third rings were fixed with transverse medial to lateral olive wires and medial-faced olive wires. All wires were tensioned to 130 kg using a standard Ilizarov technique. Methods of external fixation were placed into four groups: (1) classic Ilizarov construct, (2) Hex-Fix half-pins (Smith & Nephew, Memphis, TN, USA), (3) arced wires, and (4) steerage pins (a half pin parallel to the fracture line and below the fracture, see Fig. 2). Both the half-pin and steerage pin groups were further subdivided as described subsequently. For the proximal half-pin model, a 5-mm Hex-Fix half-pin was placed proximal to the fracture line in a perpendicular fashion to the tibia diaphysis. For the double uniplanar half-pin model, 5-mm half-pins were added sequentially above and below the fracture line at the second and third rings, respectively, in a perpendicular fashion to the tibial diaphysis. For the arced wire model, transverse wires (1.8 mm) were placed through the tibia and then fastened with cannulated fixation bolts to the second and third rings in an opposing fashion such that the concavities of their respective arcs faced toward the fracture line. These two wires were then simultaneously tensioned thereby driving the fracture ends together. For the true steerage pin construct, dual planar half-pins were attached to the second and third rings both in a manner parallel to the fracture obliquity. Hence, a virtual parallelogram is formed between the tibial axis, threaded rods of the frame, and the two parallel steerage pins (Figs. 1, 2). This technique was first described by J. Charles Taylor, MD (Taylor JC. The dynamic interfragmentary compression in oblique fractures stabilized with half pin external fixation: the steerage pin. Poster exhibit. Annual meeting of

Fig. 1 A structural parallelogram is formed between the tibial axis, the Ilizarov frame drop bar, and the steering pin pair. This model shows the fracture gap distraction to confirm that there is built in displacement of the fracture ends due to wire and half-pin placement. At the time of test, all fracture ends were apposed.

Fig. 2 This schematic illustrates the structural parallelogram and the resistance to shear forces in an oblique fracture model.

the American Academy of Orthopedic Surgeons in New Orleans, Louisiana, Feb 26, 1994). For the proximal steering pin construct, the distal steering pin was eliminated and thus, no effective parallelogram was formed.

The GP-16 sonic digitizer, distributed by Science Accessories Corporation (Stratford, CT), is an ultrasonic emitter and collector used for coordinate determination. The sonic digitizer acquires accurate three-dimensional coordinates of stationary points from a wide variety of three-dimensional structures, allowing coordinate digitization for finite element modeling and experimental modal analysis. The resolution and accuracy for each point measurement are within ± 0.1 mm. In our study, we aligned three sonic digitizer probes to measure a focal point in the X-, Y-, and Z-axes, respectively (Fig. 3). The emitter probe was calibrated to a zero reference point. Once positioning was determined, a load was placed on the tibial bone by the Bionic MTS. After each 200-N load increment, spatial positioning was recorded. A final recording was performed with a zero load to measure recoil of the focal fracture points.

The frames were initially mounted with a small fracture gap represented by the kerf of the saw blade. At the time of testing, the bone ends were accurately apposed and confirmed visually. Initially, measurement errors were identified during instrument calibration. Ambient room air motion was recognized early as the prime contributor to this error. Efforts were taken to prepare an airtight room by sealing doors, windows, and air vents with plastic covering and adhesive tape to diminish micro air motion. After appropriate room preparation, error measurements by the sonic digitizer reverted to its factory estimate of ± 0.01 mm.

We collected displacement measurements after each load interval. The FCCD represents true displacement in

Fig. 3 Sonic digitizer probes are placed at the fracture edges of the tibial fracture model. Coordinate displacement of the digitizer probe after tibial axis loading corresponds with fracture line migration.

the X, Y, and Z planes. Summation of the FCCD using Pythagorean vector analysis was then used to calculate the resultant focal point displacement in three-dimensional space. The resulting migration (or displacement) of a fracture line for three trials was averaged after loading and then abbreviated as mean fracture line migration (MFLM). Fixation models were titled after their respective modification to the classic Ilizarov construct. The classic Ilizarov construct, alone without modification, was viewed as a control for this study, and therefore data were collected from this model for all fracture obliquities. Each modality model was studied over a spectrum of fracture obliquities. As a result of their relative fracture stabilization, fixator groups with fortified modifications were sequentially added to the study with increasing fracture obliquity as these modifications were believed unnecessary in a transverse model. Data collection for the arced wire model started at 15° fracture obliquity. Both steorage pin models were used beginning at 30° fracture obliquity. Using analysis of variance on a mean of three resultant migration samples, calculations were performed for each external fixation group to determine differences between groups.

The mean standard error for each resultant displacement scalar was used for all vector analysis calculations. We determined differences in MFLM values as well as their corresponding progressions. Migration data distributed bimodally were normalized to their respective mode for trend analysis. This was used to determine the threshold angle of obliquity between fracture stability and shear force dominance. We chose up to two millimeters of MFLM as the threshold for defining construct stability.

Results

At 0° fracture obliquity (Group A), only the classic Ilizarov construct, single proximal half-pin, and double uniplanar half-pin models were studied. MFLM in these models was minimal (Fig. 4A) with the proximal half-pin model demonstrating the greatest shift (0.51 mm) after an 800-N load. There was no difference between the respective MFLM values at each axial load in the three groups. During the 1000-N axial load increment, both the classic Ilizarov construct and proximal half-pin model had a twofold increase in their respective MFLM, although the migration was limited to less than 1 mm. The arced wire model was added to the 15° obliquity model, Group B (Fig. 4B). All four models (classic Ilizarov construct, single proximal half-pin, double uniplanar half-pin, and arced wire models) maintained their respective MFLM to less than 1 mm at all loading conditions including complete loading (1000 N). Similar findings were observed at 30° of fracture obliquity (Group C, Fig. 4C). All models

restricted MFLM to less than 2 mm. The steorage pin models were added to the 40° fracture obliquity constructs (Group D, Fig. 4D). At 40° fracture obliquity (Group D, Fig. 4D), the MFLM curves demonstrated a wide but even distribution among all fixation modalities. The MFLM of the classic Ilizarov was 3 mm at 200 N. At loads 400 N and greater, the classic Ilizarov, single proximal half pin, and double uniplanar half-pin models demonstrated linear shifts of greater than 2 mm and reached their maximum MFLM of 9.0 mm (classic Ilizarov frame), 8.0 mm (single proximal half-pin), and 5.5 mm (double uniplanar half-pin) after complete loading. The single proximal steorage pin model maintained MFLM of less than 2 mm for applied loads up to 600 N. The arced wire and true steorage pin models maintained MFLM under 2 mm for all applied loads. At 50° fracture obliquity (Group E, Fig. 4E), the arced wire model maintained a MFLM of under 2 mm for loads up to 200 N only while the single proximal steorage pin model maintained a MFLM of under 2 mm for loads up to 400 N. Only the true steorage pin construct models had MFLM of less than 2 mm throughout the range of applied axial loads. At 60° fracture obliquity (Group F, Fig. 4F), the results were similar with only the true steorage pin construct maintaining a MFLM of less than 2 mm throughout.

The classic Ilizarov construct MFLM versus axial load curves demonstrated maintenance of the MFLM of less than 1 mm at fracture obliquities up to 30° (Fig. 5A). With increasing fracture obliquity (40° and greater), the MFLM exceeded 2 mm at all applied loads corresponding to a near-linear relationship between axial loading and resultant displacement. The MFLM was different ($p < 0.001$) at all applied loads (200 N to 1000 N) between the 30° and 40° degree fracture obliquities. Similarly, the MFLM curves for the single proximal half-pin and double uniplanar half pin (Fig. 5B, 5C) models demonstrated an MFLM of less than 2 mm for fracture obliquities up to 30°. Increasing obliquity was associated with increased MFLM and exceeded 2 mm for all obliquities greater than 30° with an axial load of 400 N or greater. The addition of arced wires (Fig. 5D) maintained MFLM less than 2 mm for fracture obliquities up to 40°. For the single proximal and true steorage pin constructs (Fig. 5E, F) fracture data collection was restricted to obliquities of 40°, 50°, and 60°. The addition of a single proximal steorage pin demonstrated a MFLM of less than 2 mm for 40° and 50° obliquities with lower loads (less than 400 N) but failed to restrict acceptable MFLM in higher loads and increasing obliquities. The true steorage pin construct (Fig. 5F), in which a virtual parallelogram in three-dimensional space is created, demonstrated minimal migration in all three fracture obliquities and reached a maximum MFLM of 1.16 mm.

Fig. 4A–F (A) The line graph shows the relationship between mean fracture line migration (MFLM) and fracture obliquity in the transverse model (Group A). (B) The line graph shows the relationship between mean fracture line migration (MFLM) and fracture obliquity in the 15° model (Group B). (C) The line graph shows the relationship between mean fracture line migration (MFLM) and fracture obliquity in the 30° model (Group C). Arced wires have been added. (D) The line graph shows the relationship between mean

fracture line migration (MFLM) and fracture obliquity in the 40° model (Group D). A single proximal steerage pin group and a true steerage pin construct have been added. (E) The line graph shows the relationship between mean fracture line migration (MFLM) and fracture obliquity in the 50° model (Group E). All six constructs were tested. (F) The line graph shows the relationship between mean fracture line migration (MFLM) and fracture obliquity in the 60° model (Group F). All six constructs were tested.

Discussion

When treating a fracture with external fixation, the fracture obliquity and frame design combine to influence the

composite fixator-bone construct stability. This study was designed to investigate the relationship between fracture obliquity and fracture site motion following tibial stabilization with a circular external fixator. The influence of

Fig. 5A–F (A) The line graph compares the mean fracture line migration (MFLM) for the Classic Ilizarov frame construct (four rings, eight wires). (B) The line graph compares the mean fracture line migration (MFLM) after modifying the Classic Ilizarov frame with a proximal 5 mm half-pin. (C) The line graph compares the mean fracture line migration (MFLM) after the addition of 5 mm half pins to the proximal and distal segments (double uniplanar half-pin

modification). (D) The line graph compares the mean fracture line migration (MFLM) after the addition of arced wires to the Classic Ilizarov frame. (E) The line graph compares the mean fracture line migration (MFLM) after the addition of a single proximal steerable pin. (F) The line graph compares the mean fracture line migration (MFLM) after proximal and distal steerable pins were added (true steerable pin construct modification).

frame modifications on construct stability was investigated at fracture obliquities ranging from a purely transverse pattern to 60° of obliquity.

There are several limitations to this study. We studied only coronal plane fracture obliquities. Because of the asymmetrical nature of the tibial anatomy and the appropriate location of standard wire and half pin fixation orientations, ring constructs are not totally symmetrical in their mechanical behavior. To completely understand the

relationship between obliquity and frame construct, an infinite number of models would be required. We used bone models instead of cadaveric models to ensure consistency and reproducibility. However, there were no soft tissue restraints and load was applied in a single vector.

With 2 mm as a threshold for the maximum acceptable MFLM, only a true steerable pin construct maintains acceptable fracture site motion at fracture obliquities of 50° and 60° (Fig. 6). At 40° of fracture obliquity, the true

Fig. 6 This line graph demonstrates each of the six construct configurations at each fracture obliquity.

steerage pin construct and the addition of arced wires were able to maintain an acceptable MFLM. At fracture obliquities of 30° and less, all constructs tested were able to maintain a mean fracture line migration of less than 2 mm. Compared to the classic Ilizarov construct, the addition of proximal half pins and half pins to both segments decreased the fracture site migration at 40° to 60° of obliquity, although these construct fortifications were insufficient to maintain migration of less than 2 mm. Similarly, while the addition of a single proximal steerage pin decreased fracture line migration compared to the classic Ilizarov construct for the higher fracture obliquities tested, this was insufficient to maintain MFLM less than 2 mm. Finally, the addition of arced wires demonstrated improved fracture site stability at obliquities up to 40° compared to the classic Ilizarov construct with and without the addition of half pins, but was unable to maintain adequate stability at higher obliquities.

Opposition to shear can successfully be managed by external fixation. Attention to the resultant vector force by the fixation apparatus is paramount to achieving stability. Ilizarov himself approached such an unstable fracture fragment as though it were a bicycle wheel hub floating in a mesh of loose bicycle spokes waiting to be trued. The successful application of external fixation depends on an understanding of the mechanics of fracture reduction stabilization in addition to awareness of the structural integrity of the bone-fixator composite. Whenever an oblique fracture is axially loaded, the force of opposition from the distal fragment will be distributed in both horizontal and vertical directions. Interestingly, the fracture angulation introduces two elements: incomplete opposition to the axial load and the introduction of an unopposed horizontal component of force. After the summation of the vector forces, a resultant shear force is realized. Shear force

is that which results parallel to the plane of opposition causing the contact surfaces to slide against each other. Shearing force is the culprit of instability in an oblique fracture and is exacerbated with increasing fracture angulation. Loading an oblique fracture will introduce an unopposed tangential component. Metcalfe et al. [12] attempted to characterize the role of shear in external fixation stabilization but failed to exert physiological loads in his model.

Frame stability can be modulated with the addition of half pins, altering the half pin length [12, 16], and the addition of arced wires. Other adjustments include the axial positioning of the leg inside the Ilizarov rings and the angular separation of cross wires at each ring level. Particularly for the classic Ilizarov construct, we have found increased crossing wire configuration at each fixation block, supplemented with steerage pin insertion, individually tailored to each fracture, improves stability and reduces shear. Independent of the standard external fixation mounting parameters, attention must be paid to vector force component summation and identification of the net resultant force. The aim here is to tailor frame design, supplementing opposition where it lacks, and thus recreating true limb to load equilibrium. In the case of a transverse fracture in which there is no angulation, the internal force of opposition will exhibit a force equal to and opposite its corresponding load. In the arced wire model, cross wires are fixed in an arced fashion such that their concavities face each other while surrounding the fracture line in compression. This technique provides a static form of compression because the action of the arced wires is independent of axial load. In contrast, a dynamic form of compression is applied by the true steerage pin configuration. Developed by J. Charles Taylor, MD, the steerage pin construct is a modification to the double uniplanar half-pin external fixator. In this construction, half-pins are placed parallel to the fracture line and thus in direct opposition to the shear force vector. With the previously unopposed shear force vector now in opposition, the net vector component summation equals zero, achieving equilibrium dynamically in response to the applied axial load. This is the result of the creation of a virtual parallelogram, in which its short limbs are represented by the steerage pins and the long limbs are represented by the bone itself and frame, respectively. The acute angle of the parallelogram is represented by the angle of fracture obliquity. The inherent geometric constraint of this virtual parallelogram offers a twofold advantage. First, the alignment of the steerage pins with the fracture edges provides the missing opposition needed to achieve the net zero vector summation. Second, because this virtual parallelogram meets direct opposition, the geometric constraints force the convergence of the fracture edges into compression. Thus, the shear force is

actively converted into one of compression manifesting a dynamic stabilization of the fracture edges. In this way, compression is dependent on axial load and the shear phenomenon is dramatically reduced, thereby yielding a net zero vector summation.

The clinical success following fracture treatment with external fixators is largely related to frame stability, but not necessarily stiffness. Overly rigid fixators may lead to fracture shielding, hindered bone formation, and resultant nonunion [9, 11]. The mechanical contribution of mild fracture strain has beneficial effects. Two theories have emerged describing the effects of mechanical stimuli on fracture healing. Perren and Rahn [15] described the differentiation of fracture gap tissue and how it develops in response to small interfragmentary strains [3]. Building on this, Carter et al. [2] and Blenman et al. [1] postulated that the level of vascularity as measured by hydrostatic forces is the primary stimuli determining tissue differentiation. Comparing the level of vascularity against cyclical strain stress, they formulated an equation indexing the formation of osteogenesis. Thus, from the interfragmentary strain theory bore the concept of cyclical loading. Many authors advocate mild early loading to promote strain stimuli at 3 to 6 weeks [8, 10, 13]. The mild axial pistoning, with diminution in the bending moment arm, is what creates a suitable healing environment with the Ilizarov fixator.

When treating a fracture with external fixation, the fracture configuration influences the composite fixator-bone construct stability. Defining the fracture obliquity thereby aids the surgeon in creating a more stable and biologically friendly healing environment. Optimizing the available frame modifications can minimize the fracture site motion and is especially important in increasing fracture plan obliquities. Fracture obliquities of 30° or less are adequately stabilized with a classic four-ring, eight-wire Ilizarov fixator. Increasing fracture obliquity beyond 30° caused immediate fracture instability for both the classic Ilizarov construct and unilateral half-pin models on loading. Because the arced wire model has two opposing forces to aid in fracture compression, it performs well up to 40° fracture obliquity with loading up to 1000 N. However, at 50° of fracture obliquity, the unopposed shear force dominates over the active fracture compression offered by the arced wire model, destabilizing the fracture edges as demonstrated by the large MFLM. One proximal steerable pin outperforms the double uniplanar model at 40° to 50° fracture angulation and performs best at small axial loads (less than 600 N). The true steerable pin construct demonstrated stability throughout loading over the full fracture obliquity spectrum in this study. For tibial fracture obliquities of 50° to 60°, a true steerable pin construct modification of the classic Ilizarov frame is recommended.

Clinically, the data help determine the necessary frame modifications for differing fracture obliquities. This may have implications for nonunion treatment in oblique patterns where ongoing dynamic compression across the nonunion is desired.

Acknowledgments We thank Dr Andrea Herzka for help and work in the preparation of the manuscript.

References

1. Blenman PR, Carter DR, Beaupre GS. Role of mechanical loading in the progressive ossification of a fracture callus. *J Orthop Res*. 1989;7:398–407.
2. Carter DR, Blenman PR, Beaupre GS. Correlations between mechanical stress history and tissue differentiation in initial fracture healing. *J Orthop Res*. 1988;6:736–748.
3. Cheal EJ, Mansmann KA, DiGioia AM 3rd, Hayes WC, Perren SM. Role of interfragmentary strain in fracture healing: ovine model of a healing osteotomy. *J Orthop Res*. 1991;9:131–142.
4. Draper ER, Wallace AL, Strachan RK, Hughes SP, Nicol AC, Paul JP. The design and performance of an experimental external fixation device with load transducers. *Med Eng Phys*. 1995;17:618–624.
5. Duda GN, Sollmann M, Sporrer S, Hoffmann JE, Kassi JP, Khodadadyan C, Raschke M. Interfragmentary motion in tibial osteotomies stabilized with ring fixators. *Clin Orthop Relat Res*. 2002;396:163–172.
6. Gardner TN, Hardy JR, Evans M, Richardson JB, Kenwright J. The static and dynamic behaviour of tibial fractures due to unlocking external fixators. *Clin Biomech (Bristol, Avon)*. 1996;11:425–430.
7. Gardner TN, Simpson H, Kenwright J. Rapid application fracture fixators—an evaluation of mechanical performance. *Clin Biomech (Bristol, Avon)*. 2001;16:151–159.
8. Geller J, Tornetta P 3rd, Tiburzi D, Kummer F, Koval K. Tension wire position for hybrid external fixation of the proximal tibia. *J Orthop Trauma*. 2000;14:502–504.
9. Goodship AE, Watkins PE, Rigby HS, Kenwright J. The role of fixator frame stiffness in the control of fracture healing. An experimental study. *J Biomech*. 1993;26:1027–1035.
10. Jaskulka RA, Egkher E, Wielke B. Comparison of the mechanical performance of three types of unilateral, dynamizable external fixators. An experimental study. *Arch Orthop Trauma Surg*. 1994;113:271–275.
11. Kummer FJ. Biomechanics of the Ilizarov external fixator. *Bull Hosp Jt Dis Orthop Inst*. 1989;49:140–147.
12. Metcalfe AJ, Saleh M, Yang L. Techniques for improving stability in oblique fractures treated by circular fixation with particular reference to the sagittal plane. *J Bone Joint Surg Br*. 2005;87:868–872.
13. Ostrum RF, Litsky AS, Anson LW. Limited internal fixation of the tibia with external fixation: an in vivo canine study. *J Orthop Trauma*. 1994;8:50–53.
14. Park SH, O'Connor K, McKellop H, Sarmiento A. The influence of active shear or compressive motion on fracture-healing. *J Bone Joint Surg Am*. 1998;80:868–878.
15. Perren SM, Rahn BA. Biomechanics of fracture healing. *Can J Surg*. 1980;23:228–232.
16. Roberts CS, Dodds JC, Perry K, Beck D, Seligson D, Voor MJ. Hybrid external fixation of the proximal tibia: strategies to improve frame stability. *J Orthop Trauma*. 2003;17:415–420.