

Effect of Wire Tension on Stiffness of Tensioned Fine Wires in External Fixation: A Mechanical Study

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Abstract

To determine the effect of changes in magnitude of transfixion wire tension on stiffness of fine-wire external-fixation load deformation, we compared results obtained with different wire tensions (50-140 kg) under identical conditions of central axial compression, medial compression-bending, posterior compression-bending, posteromedial compression-bending, and torsion. Stiffness values were calculated from the load-deformation and torque-angle curves. Tension of 140 kg provided the most stiffness, and there was a trend toward increasing overall stiffness with increasing wire tension. The 1.8-mm wires should be tensioned to at least 110 kg in most cases of fine-wire external fixation; compared with all tensions less than 110 kg, this tension provides significantly more mechanical stability in all loading modes.

The stiffness of a fracture-fixation device is an important determinant of treatment outcome. The mechanical properties of an external-fixation frame, used to treat any bone pathology, determine the biomechanical environment in the healing bone gap.¹⁻⁴ Although Ilizarov⁵ considered an unfavorable biomechanical environment to be the main cause of nonunions, biological failure in bone healing often results from inadequate mechanical stability of the fractured bone ends in the early weeks of osteoneogenesis.⁶

Tensioned wire techniques have long been used with Kirschner wires (K-wires) for skeletal traction.⁷ The Ilizarov ring fixator and, later, other ring external fixators popularized use of tensioned wires.¹⁻⁵ Fixators with tensioned fine wires have increasingly been used in orthopedics.^{4,5,8,9} Many wire variables affect the stiffness of external fixation: wire tension, wire number, wire diameter, wire positioning, wire orientation, wire design, and so forth. Transfixion wire tension appears to be an important factor in the overall stiffness of ring and hybrid external fixation.^{7,10,11} Wire tension is directly related to wire length, wire diameter, yield point, load, number of wires per ring, wire orientation, wire holders, ring diameter and pattern, and tension method.^{3,10,11} Although wire tensions ranging from 30 to 130 kg have been reported,^{4,5,8-11} the most popular tensions seem to range from 90 to 130 kg.^{5,9-11}

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Numerous biomechanical studies of external fixation have been performed,^{1-4,12-14} but only a few studies on the direct effect of wire tension on fracture fragment stability have been reported.^{4,13-15} The purpose of the study reported here was to evaluate the effect of changes in magnitude of transfixion wire tension on the stiffness of the fixation of the proximal tibia.

MATERIALS AND METHODS

Experimental Design

In this laboratory investigation, we used fiberglass composite tibias (Pacific Research Laboratories, Vashon Island, Wash) fixed into an idealized test frame. The purpose of the idealized frame was to eliminate frame deformation, so the influence of the wires' behavior alone could be studied.

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Table I. Stiffness of Wire Tensions in 5 Testing Modes

Wire Tension (kg)	Testing Mode				
	Central (N/mm)	Medial (N/mm)	Posterior (N/mm)	Posteromedial (N/mm)	Torsion (N-m/°)
50	87.3±0.66	52.3±0.45	29.8±0.58	25.4±0.29	2.2±0.11
60	88.6±0.61	53.4±0.48	31.1±0.1	25.7±0.17	2.7±0.46
70	96.5±0.86	57.6±0.21	33.4±0.32	28.6±0.23	3.2±0.12
80	100.4±1.8	61.6±0.45	33.2±0.25	29.2±0.08	3.2±0.08
90	105.7±1.33	64.1±1.76	35±0.4	29.6±0.3	3.9±0.42
100	106.7±2.18	68.9±0.65	37±0.5	30.4±0.12	4.1±0.16
110	131.3±1.84	75±0.78	40.7±0.45	34±0.2	5.3±0.63
120	137.5±3.69	82.9±2.19	40.8±0.4	34.6±0.5	5.2±0.03
130	144.9±6.67	90.5±5.24	44.4±0.61	35.5±0.15	5.2±0.33
140	157.8±5.08	98.7±4.1	46.7±1.17	36.4±0.15	6±0.57

Table II. Loading Modes for Which Significant Differences (*P*<0.05) Were Found Between Wire Tensions*

kg	kg									
	50	60	70	80	90	100	110	120	130	140
50	●				C,M,P,T	M,P,T	C,M,P,PM,T	C,M	C,M,P,PM,T	C,M,P,PM,T
60		●			C,M,P,T	M,P,T	C,M,P,PM,T	C,M	C,M,P,PM,T	C,M,P,PM,T
70			●		C,M,P,T	M,P,T	C,M,P,PM,T	C,M	C,M,P,PM,T	C,M,P,PM,T
80				●	C,M,P,T	M,P,T	C,M,P,PM,T	C,M	C,M,P,PM,T	C,M,P,PM,T
90					●	M,P,T	C,M,P,PM,T	C,M	C,M,P,PM,T	C,M,P,PM,T
100						●	C,M,P,PM,T	C,M	C,M,P,PM,T	C,M,P,PM,T
110							●	C,M	C,M,P,PM	C,M,P,PM,T
120								●	C,M,P,PM	C,M,P,PM,T
130									●	C,M,P,PM,T
140										●

*C indicates central; M, medial; P, posterior; PM, posteromedial; T, torsion.

Specimen Preparation

The test model was a third-generation composite tibia manufactured to the material and geometrical specifications of a human tibia (Pacific Research Laboratories, Vashon Island, Wash). The tibia was fixed into the most proximal ring of an idealized frame (Figure 1) using 2 K-wires, each 1.8 mm in diameter (Smith & Nephew, Memphis, Tenn). These wires were inserted 18 mm and 20 mm below the articular surface and were crossed at 60°, the angle most appropriate for periarticular fixation. The wires were crossed in the center of the tibia, with the tibia centered in the ring. The distal end of the tibia was not fixed. Loading was applied through a custom plate mounted on the tibial plateau (Figure 1). A load cell (Model 661.19 E-01, 5000 N capacity, MTS Systems Corporation, Eden Prairie, Minn) was connected to the idealized frame (Figure 1) to measure wire tension. One end of the wire was clamped to the load cell, and the Ilizarov tensioner (Smith & Nephew, Memphis, Tenn) was used to apply tension through the other end. With this arrangement, the wire tension could be precisely controlled to minimize tensioning errors.¹⁰ After the wire was tensioned, it was secured in the ring using 2 set screws on each end. Markers on each wire were observed to detect any gross wire slippage. In cases of slippage, the wires were retensioned and the tests repeated. New wires were used whenever wire damage was noted.

Mechanical Testing Protocol

Loads were applied under displacement control through the load plate (Figure 1) using a servohydraulic load frame (Bionix 858, MTS Systems Corporation, Eden Prairie, Minn). Five loading regimens were used: central compression, medial compression, posterior

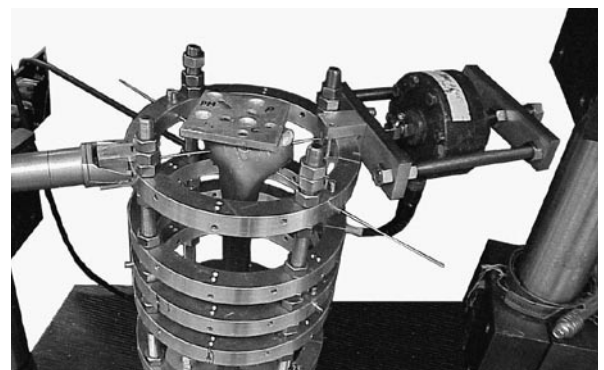


Figure 1. The test model, a fibreglass composite tibia (Pacific Research Laboratories, Vashon Island, Wash) fixed in the most proximal ring of idealized fixator using 2 crossed (at 60°) transfixion 1.8-mm wires (Smith & Nephew, Memphis, Tenn). The distal end of the fibreglass tibia was not fixed. A force transducer (load cell) device was connected to the idealized frame. One end of the wire was connected to the force transducer; the other end was tensioned with the Ilizarov tensioner (Smith & Nephew, Memphis, Tenn). The loading was accomplished through a custom plate mounted on the tibial plateau.

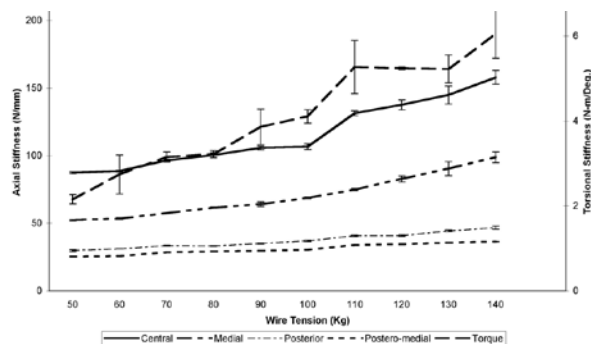


Figure 2. Stiffness of wire tensions in 5 testing modes.

compression, posteromedial compression, and torsion. Displacement of the actuator was recorded for each test at 100 N load of compressive force and 5 N-m of torque in both directions. Loads of 100 N (50 N per wire) were used to simulate light, “toe-touch” weight-bearing. The proximal load plate offset the medial and posterior loading by 4 cm, resulting in 4 N-m of bending in those loading modes. The posteromedial loading resulted in 5.66 N-m of bending.

We tested 5 separate bones 5 times each for each tension value in each loading pattern. Test order was randomized for each bone. Wires were loosened and retightened before each test.

Data Analysis

We compared the stiffness values (determined from load vs deformation behavior) of the different tensions and load configurations. Analysis of variance

been distinctly identified as a crucial factor in overall stiffness.^{4,10,11,14} In the present study, we found that increasing wire tension contributes to an increase in wire-related fixation stiffness. Our simple model allowed evaluation of axial stiffness, torsional stiffness, and bending stiffness in the sagittal plane, in the coronal plane, and in the 45° oblique plane between the sagittal and the coronal planes. Such methodology is analogous to bone loading during physiologic conditions in which the bone is much exposed to eccentric compression-bending rather than 3- or 4-point bending. Medial combined compression-bending was simulated because of the medial offset of the body’s center of gravity over the tibia. Posterior combined compression-bending was simulated because of the powerful sagittal plane muscle forces acting on the tibia. The model is easy to reproduce, and data collection is kept simple to minimize variability from test to test. A rigid test frame was used to isolate the behavior of the wires so that their contribution could be analyzed independently.^{16,17}

Kummer¹⁴ noted that increasing wire tension increases the rigidity of the fixator nonlinearly. Increasing the tension from 60 to 120 kg accounted for an increase in stiffness of only 10%.^{14,15} With use of a rigid frame in our study, a wire tension increase from 60 to 120 kg accounted for a larger increase (53%) in stiffness, and there was more linearity in the relationship between wire tension and stiffness. For testing, Gasser and colleagues¹⁵ used an intact Ilizarov frame consisting of 8 crossed wires fixed to 4 rings. Ring deformation cannot be underestimated as a factor in maintaining wire ten-

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and post hoc *t* tests with a set at $P < 0.05$ were used to compare the stiffness values corresponding to the tension values.

RESULTS

Stiffness results appear in Table I and Figure 2. In all loading modes, significantly more stiffness was provided by higher wire tensions than by lower wire tensions. Specific statistically significant differences are listed in Table II. With wire tension being increased, the first tension level that provided significantly more stiffness than that provided by all lower tension levels in all loading modes was 110 kg.

DISCUSSION

The mechanical characteristics of the external fixator represent one of the major factors that determine the biomechanical environment at a fracture or osteotomy site and thereby affect healing.^{1,2,4,11} Wire tension has

sion.³ Tensioned wires deform the Ilizarov rings. The Ilizarov frame allows 3.5 to 58 times more deformation than our idealized frame. We believe that the nonlinear relationship between wire tension and stiffness is more the result of frame deformation and the variables affecting wire tension than the result of wire behavior. According to Kummer,¹⁴ who studied the effect of tensioning a single wire on axial stiffness (1.8-mm wire, 150-mm ring), doubling wire tension from 60 to 120 kg produced a 33.3% increase in stiffness, which is closer to our data (taking into account the difference in ring diameter and ring stiffness).

The yield point is the point at which a wire plastically deforms or permanently stretches in tension. Plastic deformation of a wire can seriously compromise the stability of a construct. The yield point for the typical K-wire is 120 kg/mm², which equals 210 kg for a 1.5-mm wire and 305 kg for a 1.8-mm wire.^{3,12} Optimal wire tension

is no more than 50% of the yield strength of the wire.¹² We used the recommendations of Paley¹² in our study and tensioned the 1.8-mm wires to a maximum of 140 kg. The baseline tension in a wire is increased by deflection during treatment, creating an additional working tension. The working tension may actually approach yield. To avoid permanent gross wire deformation or wire slippage, we did not tension the wires at higher levels.

Stiffness of a tensioned wire is limited by its yield point and the tension-holding capacity of the wire connection bolts.^{3,18} Aronson and Harp³ indicated that wire tension of 1250 N (127 kg) and bolt torque of 20 N-m represent the safe and reliable upper limits for 1.8-mm

When possible, surgeons should tension 1.8-mm wires to 140 kg to maximize stability of external fixation. The goal should be to achieve and maintain tension of at least 110 kg, which provides a significant increase in fixation stiffness and helps avoid permanent wire deformation and slippage.

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wires. They found that wire tension above those limits cannot be maintained unless the nuts are tightened to a level that may result in bolt failure. Kummer¹⁴ reported maximum limits of 90 kg for 1.5-mm wires and 130 kg for 1.8-mm wires—reflections of the yield strength of stainless steel and of slippage at wire holders. Mullins and colleagues¹⁹ demonstrated that many bolt/wire fixations are at the point of failing even after initial wire tensioning because bolt torque of 20 N-m is extremely close to the torque at which the bolts shear and is almost impossible to achieve under clinical conditions. They recommended a torque of at least 10 N-m for each locking nut, but their data showed that this torque was close to the torque at which the wire slipped under the initial wire tension of 130 kg. Watson and colleagues²⁰ demonstrated that clamping a 1.8-mm tensioned wire could cause a 22% reduction in wire tension, which was correlated with the deformation caused by the bolts. Our data support this observation. The behavior of our 2-wire constructs tended to plateau beyond the tension level of 110 kg. Although the cause (either small amounts of wire slippage or wire yield) is unclear, many of the higher tension tests did not differ significantly from the 110-kg tension tests.

The weaknesses of our study are that we did not investigate all variables influencing wire tension and that our results have not been validated in clinical trials. The strengths of our study include using an idealized frame that excluded frame deformation, keeping constant the variables affecting wire tension, and testing only the influence of changes in wire tension on the stiffness of external fixation. Wire tension was measured with a force transducer (load cell) device, which minimized tensioning errors. We also prevented wire slippage by securing wires with 2 bolts at each end and by using markers on each wire. In addition, we used a strict, reproducible testing protocol in which the wires were retensioned between tests.

Increasing wire tension contributes to an overall increase in stiffness of fine-wire external fixation.

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