Stabilization of a Short Juxta-Articular Bone Segment with a Circular External Fixator

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Summary: The objective of the current study was to evaluate the stabilization of a simulated juxta-articular bone segment with a circular external fixator, and to determine which method of fixation improved bending stabilization while preserving the axial dynamization of a three-wire configuration. Frames were divided into three groups: wire, half-pin and hybrid and tested in axial compression, torsion, anteroposterior bending and mediolateral bending. Hybrid frames using 4 mm half-pins improved the anteroposterior stabilization of the short bone segment while maintaining axial characteristics similar to a three-wire frame. Increasing the bending stabilization will improve bone segment alignment while permitting axial micromotion beneficial to bone healing. *J Pediatr Orthop B* **11**:143–149

Key Words: Ilizarov—Hybrid—Biomechanics—Orthopaedics—Stiffness.

Circular external fixation has become a renowned technique for upper and lower limb lengthening, deformity correction, and filling of long bone defects. The osteotomy for these cases is typically performed in the metaphyseal area of the affected extremity resulting in a short juxta-articular bone segment. This segment is usually subjected to large forces generated by muscle tension, joint movement, and weight bearing.

Based on extensive experimental and clinical studies, Ilizarov (22,23), and later, other investigators (24,31,34,35) demonstrated that circular external fixation using thin tensioned crossed transfixing wires provided excellent stabilization and controlled three-dimensional manipulation of bone segments during the correction process. Ilizarov determined that ideal fixation of a bone segment could be achieved with two levels of fixation using three wires (90° wire angle at one level and a single bisecting wire at the second level). He determined that this frame configuration resisted muscle forces and maintained an ideal environment for bone healing and regeneration. An important characteristic of this frame is the beneficial axial micromotion of the bone segments, which is approximately 1 mm in most cases (18,19,23,25).

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Due to anatomical considerations this 'ideal' bone fixation frame is only applicable in the distal tibia. In other locations, anatomy of the upper and lower extremities dictates much smaller wire angles in the mediolateral direction (45° to 60° for the distal femur or proximal tibia and 30° to 45° for the proximal femur and humerus).

Numerous biomechanical studies demonstrate that frame configurations with wire angles less than 90° decrease the anteroposterior bending stiffness, especially when stabilizing short bone segments (8,28,29). Increasing the number of wires per bone segment (i.e., two pairs of cross wires) still does not substantially improve anteroposterior bending stiffness, even when wires with stoppers (olive wires) are used. To alleviate these problems, half-pin fixation of the proximal femur and humerus, and the combination of half-pins and wires for the fixation of the proximal tibia, humerus and distal femur are often used clinically (2,5,10,11, 13,16,17,20,32,36).

Biomechanical studies (7) have demonstrated that half-pin and hybrid constructs substantially increase the stiffness of the circular external fixator in all modes of loading (20,39). The objective of the current study was to determine frame configurations that improved bending stabilization of a short juxta-articular bone segment while maintaining axial dynamization similar to a three-wire configuration.

MATERIALS AND METHODS

A standard two-ring block consisting of two stainless steel 150 mm rings with a 20 mm separation was used for biomechanical testing.

A solid 38 mm diameter Delrin cylinder (Dupont, Wilmington, Denver, USA), simulating a bone segment, was centrally positioned in the rings. Guide holes of 1.7 mm and 3.0 mm were drilled in the Delrin bone model to accept 1.8 mm K-wires or 4 mm and 5 mm threaded half-pins respectively and to ensure adequate 'bone'/wire or 'bone'/half-pin interface. All wires were tensioned to 130 kg with a dynamometric wire tensioner. Rings were designated as having anterior, posterior, medial, and lateral sides to simulate the clinical orientation of the fixation elements. All fixation components (rings, wires, half-pins, bolts, etc.) and tensioners were from Smith & Nephew Richards Inc. (Memphis, TN, U.S.A.).

Frames were divided into three fixation groups: wire, half-pin and hybrid. Each group had three different frame configurations. The wire fixation group (Fig. 1) included two three-wire configurations (W1 and W2) with a wire angle of 45° or 90° on one ring and a single wire on the other ring bisecting the wire angle on the first ring. The four-wire configuration (W3) had two pairs of wires inserted at 90° to each other on both rings.

In the half-pin group (Fig. 2), two-pin and three-pin configurations were examined. The first (P1) consisted of two half-pins inserted at 90° to each other (each 45° to the anteroposterior axis) on one ring. The second configuration (P2) consisted of two half-pins inserted on the lateral aspect, with one pin on each ring. The third frame (P3) consisted of three pins: two half-pins similar to the first half-pin frame with an additional half-pin inserted on the anterior aspect of the second ring.

Hybrid frames (Fig. 3) incorporated the use of both wires and half-pins. The first configuration (H1) had two wires with a 45° crossing angle on the first ring and a single half-pin inserted on the anterior aspect of the second ring. The second construct (H2) had two half-pins on the first ring, inserted 90° to each other (each 45° to the anteroposterior axis), and a single wire inserted mediolaterally on the second ring. The third frame (H3) consisted of a single wire inserted obliquely (45° to the anteroposterior axis) on the first ring and two half-pins positioned on the anterior and medial aspect of the second ring.

Mechanical testing was performed on a universal testing system (MTS Systems Corp., Eden Prairie, MN, USA) in axial compression, torsion, anteroposterior bending, and mediolateral bending. Loads were applied to the Delrin bone model at a distance of 100 mm from the wire/bone or pin/bone interface (Fig. 4). Constructs were loaded to 550 N (18.5 N/sec), 11.3 N · m (0.4 N · m/sec), and 50 N (1.6 N/sec) in axial compression, torsion, and bending, respectively. Each construct was tested four times in each loading mode and the load/displacement curves were plotted on an X-Y plotter (VP-6424S, Soltec Corp., Sun Valley, CA, USA). The linear portion of each load/displacement curve was analyzed to determine the stiffness characteristics in all four loading modes. Resulting stiffness values are presented as N/mm for axial compression and bending, and N · mm/° for

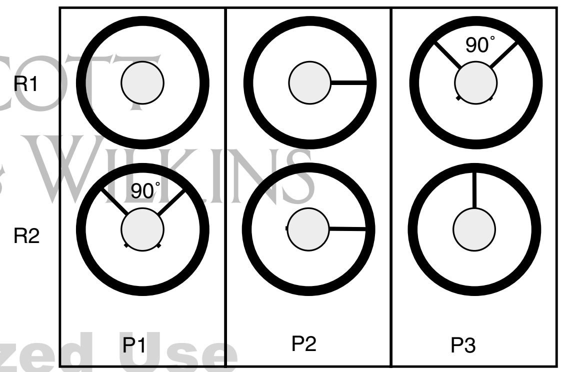

FIG. 2. Construct configuration for the half-pin fixation group.

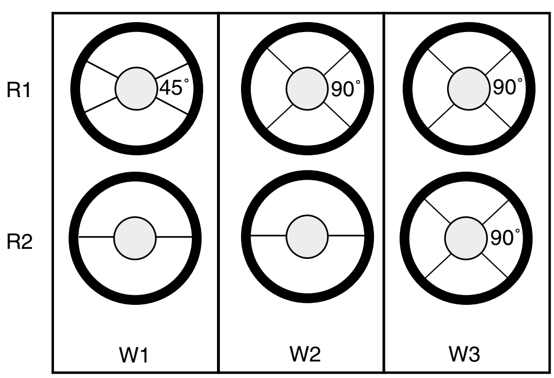

FIG. 1. Construct configurations for the wire fixation group.

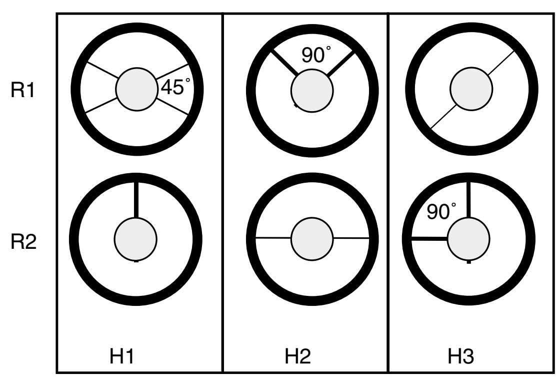

FIG. 3. Construct configuration for the hybrid fixation group.

torsion. Statistical analysis was performed using the SYSTAT 8.0 (SPSS Inc., Chicago, IL, USA) software, using a one-way analysis of variance (ANOVA). The five fixation groups (wire, 4 mm and 5 mm hybrid and 4 mm and 5 mm half-pin) were compared and a Tukey multiple comparison post-hoc test was used to determine the level of significance ($P = 0.05$) between groups. Averaged stiffness values of the individual frame configurations were compared to the three-wire (W1) construct to determine the percent change in stiffness for each mode of loading.

RESULTS

Axial compression

Axial compression testing indicated that the insertion of additional fixation elements, either wire or half-pin, improved axial stiffness (Fig. 5). Statistical analysis determined that there was a significant difference between the 4 mm and 5 mm hybrid groups ($P < 0.005$) and the 4 mm hybrid and the 5 mm half-pin groups ($P < 0.005$).

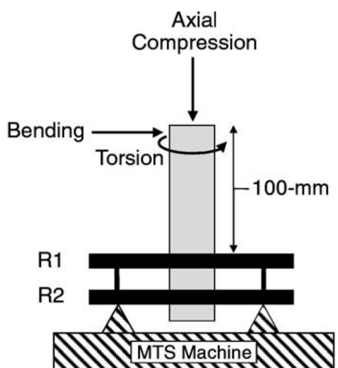

FIG. 4. Frame set-up for mechanical testing, R1 and R2 refer to the ring position.

All frames with 5 mm half-pins increased axial stabilization by as much as 39% compared with the three-wire frame (Table 1). The 4 mm half-pin frames were less stable axially than the 3-wire frame by as much as 40% while the 4 mm hybrid frames provided axial stabilization equivalent to the three-wire configuration. The use of 5 mm half-pins increased axial stabilization by an average of 25% compared with the 4 mm half-pins.

Torsion

For all frames examined, torsional stiffness increased with the insertion of additional fixation elements (Fig. 6).

All hybrid frames provided equivalent or increased torsional stabilization of the bone segment compared to the three-wire frames (Table 1). Five millimetre half-pins increased torsional stabilization by an average of 25% compared with 4 mm half-pins.

Anteroposterior bending

Anteroposterior bending stabilization of the bone segment was increased by the insertion of fixation elements in the plane of bending (Fig. 7).

All frames examined were more stable than the three-wire configuration (Table 1). The third half-pin frame (P3). using either 4 mm or 5 mm half-pins, increased anteroposterior bending stabilization by over 90% compared with the three-wire frame (W1).

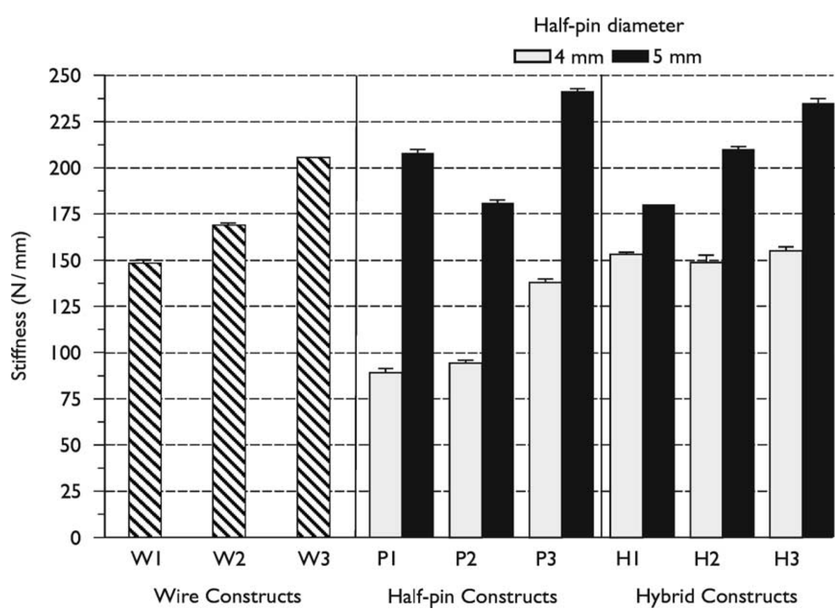

FIG. 5. Axial compression stiffness for each construct configuration.

TABLE 1. *Change in stiffness for each mode of testing with respect to the three-wire (W1) frame*

Group		Pin diameter	Axial compression (%)	Torsion (%)	A-P bending (%)	M-L bending (%)
Wire	W1		0	0	0	0
	W2		12	5	46	−10
	W3		28	10	63	−15
Half-pin	P1	4 mm	−40	−10	6	12
		5 mm	29	29	53	52
	P2	4 mm	−36	−68	29	80
		5 mm	18	−43	65	79
	P3	4 mm	−7	25	91	38
		5 mm	39	41	94	51
Hybrid	H1	4 mm	3	0.2	66	−24
		5 mm	18	11	68	−5
	H2	4 mm	0.2	15	62	29
		5 mm	29	38	73	55
	H3	4 mm	4	29	54	−17
		5 mm	37	38	70	26

A-P, anteroposterior; ML, mediolateral

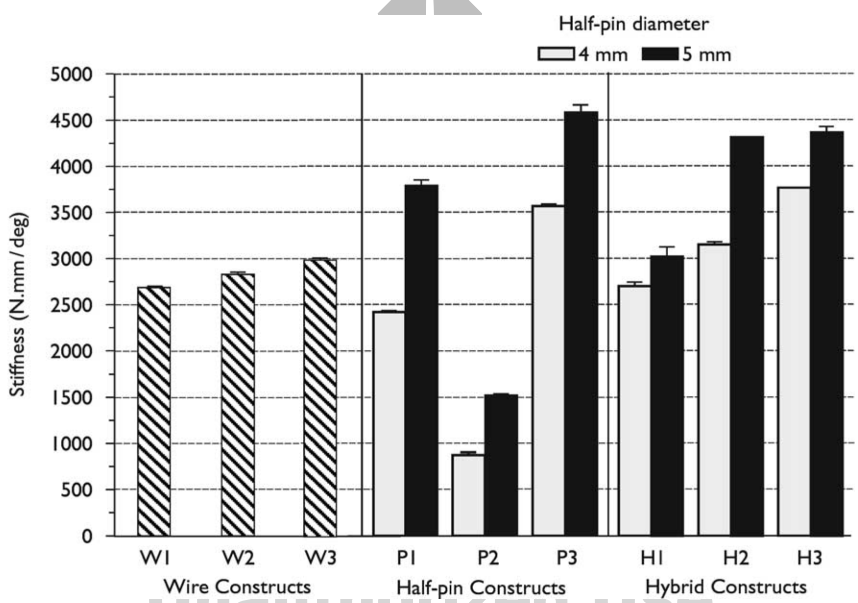

FIG. 6. Torsion stiffness for each construct configuration.

Anteroposterior bending stabilization increased by approximately 30% with 5 mm half-pins compared with 4 mm half-pins.

Mediolateral bending

Mediolateral bending stiffness demonstrated the same characteristics as seen with anteroposterior bending. Stabilization in the mediolateral direction was improved with insertion of fixation elements in the plane of bending (Fig. 8).

All 4 mm and 5 mm half-pin frames were more stable than the three-wire configuration. The second hybrid frame (H2) and third hybrid frame (H3) using 5 mm half-pins were more stable under mediolateral loading than the three-wire frame. The first hybrid frame (H1) and the third hybrid frame (H3) using 4 mm half-pins provided less mediolateral bending stabilization than the three-wire configuration. Mediolateral bending stabilization increased by an average of 30% with 5 mm half-pins compared with 4 mm half-pins.

DISCUSSION

Stabilization of bone segments by circular external fixation is an important parameter affecting new bone formation and remodeling during fracture healing and distraction osteogenesis (3,4,12,19,22,42). Controlled axial micromotion stimulates healing while off-axis motion of the bone segments may delay bone

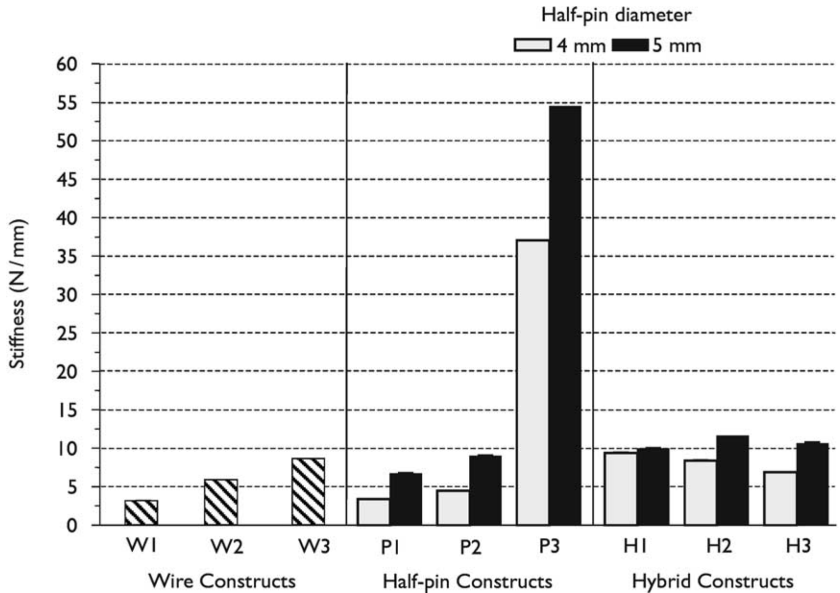

FIG. 7. Anteroposterior bending stiffness for each construct configuration.

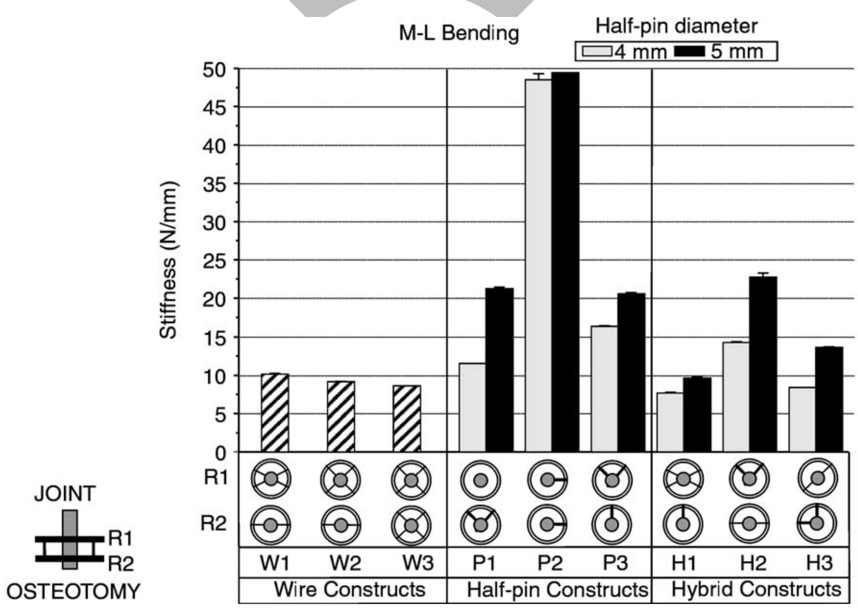

FIG. 8. Mediolateral bending stiffness for each construct configuration.

tissue regeneration. Therefore, ideal bone segment stabilization should permit axial micromotion, while maintaining adequate torsion and bending stability.

Wire fixation of a bone segment using circular external frames is notable for the ability to achieve excellent stabilization, while allowing axial micromotion (33). Optimal fixation may be achieved if the divergence angle between the wires is close to 90° (1,8,9,14,26,28,30). However, anatomical considerations such as the presence of muscles, tendons, and neurovascular structures (37) often prevent the use of a 90° angle. Smaller wire angles are typically required in the distal femur, proximal tibia, and distal and proximal humerus. Clinical experience has demonstrated that these smaller wire angles have insufficient anteroposterior stability to resist off-axis motion generated by muscles (6), even when additional wires or wires with stoppers are used. For example, a proximal tibia juxta-articular segment has a tendency for a medial and anterior translation resulting in valgus and procurvatum deformity during lengthening.

The use of half-pins alone or in conjunction with wires has been endorsed to improve bone segment stabilization, while reducing soft tissue impingement particularly in the popliteal area (2,5,10,13, 16,17,20,27,40). However, larger diameter half-pins may increase the axial stiffness of the frame and reduce the beneficial axial micromotion seen in wire constructs. Therefore, the current study mechanically examined several wire, half-pin, or hybrid frames to determine which stabilization method would improve the bending stability of a small bone segment while maintaining the axial micromotion similar to the three-wire frame and potentially minimizing soft tissue encroachments.

Results of the present study confirmed that the insertion of 4 or 5 mm half-pins on the anterior or posterior aspect of the frame substantially increase anteroposterior bending stability. Five millimetre half-pins inserted alone or in any combination with wires created an axial stiffness significantly (18%–37%) higher than that generated by three wires. The use of 4 mm half-pins alone substantially reduced the axial stiffness compared to that generated by three wires. However, the use of 4 mm half pins in conjunction with wires provided axial stability similar to three-wire constructs.

The effect of torsional motion on fracture healing has not been extensively examined. While there have been no reports of fracture healing failure with the use of circular fixation, studies of intramedullary fixation of fractures (21,38,41) indicate that lower torsional stabilization resulted in increased callus formation and a higher rate of nonunion. In the current study, all hybrid frames and half-pin frames except the 4 mm half-pin type (P1) and the 4 mm and 5 mm half-pin type (P2) provided equivalent or higher torsional stabilization to the three-wire frames.

Waanders et al. (39), devised a simple method to determine the axial stiffness of a hybrid frame by the number of wires, half-pins and ring diameter. Using the estimation graphs developed in that study, a hybrid frame using a 150 mm ring, one 1.8 mm wire, and two 5 mm half-pins should have an axial stiffness of 49 N/mm, which is over three times lower than what was determined in our study. Comparing the results of other biomechanical studies of circular fixation to this estimation technique produced similar results (8,30). The axial stiffness values were underestimated by an average of 58% (30%–83%) when compared with the values obtained through mechanical testing of the frames. Waanders' estimation method assumes equal load sharing between half-pins and wires. However, tests in our biomechanics laboratory have demonstrated that a single 5 mm half-pin has equivalent stiffness to two wires (1.8 mm, 130 kg of tension) with values of 85 N/mm and 90 N/mm, respectively. The higher stiffness of the half-pin dictates that there will not be an equal load sharing between the wires and half-pins. The nonlinear characteristics of tensioned wires under axial compression (8,15,30) also illustrates that, for lower axial loads, the half-pins will provide most of the stabilization until the half-pins deflect enough to allow the wires to provide some additional stabilization.

Interestingly, there was no significant difference ($P > 0.99$) between the 5 mm half-pin and 5 mm hybrid constructs in axial stiffness. This indicates that the 5 mm half-pins minimize the contribution of the wires to axial stiffness. Alternatively, the axial stiffness of a 4 mm hybrid frame was on average 30% higher than a 4 mm half-pin construct. Thus, for 4 mm hybrid constructs, both half-pins and wires contribute to the axial stabilization of the bone segment. This load sharing between the 4 mm half-pins and tensioned wires permits axial micromotion to be maintained while improving bending stabilization. The 4 mm hybrid constructs had axial stiffness values that were not significantly different from that of the three wire constructs but anteroposterior bending stiffness values that were 50% higher than the three-wire configuration.

The clinical application of these hybrid constructs is dependent upon the anatomy of the limb segment. For example, a hybrid configuration which has two wires inserted at 30° to 45° angle bisected by a single half pin (H1) can be useful for fixation of the proximal humerus. The configuration consisting of two half-pins inserted with a 90°-divergence angle and a single wire are applicable for both the proximal tibia and distal femur. In the proximal tibia, half-pins inserted on the anterior aspect of the tibia will avoid impinging the posterior soft tissue compartment (6). In the distal femur, the half-pins inserted posteriorly will leave the suprapatellar pouch free of fixation elements minimizing potential fibrosis.

There are several limitations to the current study. Although intrinsic factors, such as that soft tissue tension and bone regenerate stiffness, provide substantial contribution to overall bone fragment stabilization (23) this study specifically focused on the extrinsic factors of half-pin diameter and fixation element positioning. In clinical situations, variations in bone geometry and mechanical properties will inherently affect the overall stability of fixation. The use of a uniform cylinder as a bone model eliminated this variability and allowed an investigation of only those factors that can be directly controlled during frame application. In addition, the 5 mm half-pin will be able to withstand higher loading and failure due to cyclic loading than 4 mm half-pins. While these factors were not examined in this study they are important and must be taken into account during frame application decisions.

In conclusion, use of the smaller diameter 4 mm half-pins may allow the surgeon to substantially improve the anteroposterior bending stabilization of a short juxta-articular bone segment while maintaining the beneficial axial dynamization seen with the three-wire constructs.

Acknowledgements: Supported by the Texas Scottish Rite Hospital for Children Research Fund.

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