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Analysis of strategies to increase external fixator stiffness: Is double stacking worth the cost?

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ABSTRACT

We compared the mechanical benefits and costs of 3 strategies that are commonly used to increase knee-spanning external fixator stiffness (resistance to deformation): double stacking, cross-linking, and use of an oblique pin. At our academic trauma centre and biomechanical testing laboratory, we used ultra-high-molecular-weight polyethylene bone models and commercially available external fixator components to simulate knee-spanning external fixation. The models were tested in anterior–posterior bending, medial–lateral bending, axial compression, and torsion. We recorded the construct stiffness for each strategy in all loading modes and assessed a secondary outcome of cost per 10% increase in stiffness. Double stacking significantly increased construct stiffness under anterior–posterior bending (109%), medial–lateral bending (22%), axial compression (150%), and torsion (41%) ($p < 0.05$). Use of an oblique pin significantly increased stiffness under torsion (25%) ($p < 0.006$). Cross-linking significantly increased stiffness only under torsion (29%) ($p < 0.002$). Double stacking increased costs by 84%, cross-linking by 28%, and use of an oblique pin by 15% relative to a standard fixator. All 3 strategies increased stiffness under torsion to varying degrees, but only double stacking increased stiffness in all 4 testing modalities ($p < 0.05$). Double stacking is most effective in increasing resistance to bending, particularly under anterior–posterior bending and axial compression, but requires a relatively high cost increase. Clinicians can use these data to help guide the most cost-effective strategy to increase construct stiffness based on the plane in which stiffness is needed.

Introduction

External fixation spanning the knee is commonly applied to treat periarticular fractures, such as proximal tibial and distal femoral fractures, before definitive fixation is applied. The surgeon is faced with conflicting goals of attaining increased construct stiffness while avoiding pin insertion into the zone of injury and sites of future fracture fixation. For inherently unstable fractures without cortical apposition, it can be a challenge for the surgeon to provide adequate stabilization while maintaining acceptable fracture alignment. It is a relatively common problem to have an external fixator in place that is not stable enough to hold the reduction, requiring the surgeon to improve the fixator construct stiffness or to accept a non-ideal reduction that might compromise the soft-tissue envelope and increase risk to the ultimate surgical approach.

To our knowledge, no previous biomechanics work has assessed knee-spanning external fixators to help guide clinicians' strategy in such situations. Few data are available regarding more modern external fixators. The classic studies of external fixation systems are almost 30 years old [1–6]. Those and other studies [1,2,5–11] have examined only tibial shaft fractures and have defined our current practices regarding parameters such as pin diameter and clamp-to-bone distance. These parameters typically are already optimized in the clinical setting, thereby leaving the clinician with little guidance for increasing frame stiffness.

We compared 3 commonly used methods of increasing the construct stiffness (resistance to bending) of a knee-spanning external fixator. We also determined the cost of each strategy. Our hypothesis was that with a knee-spanning external fixator model,

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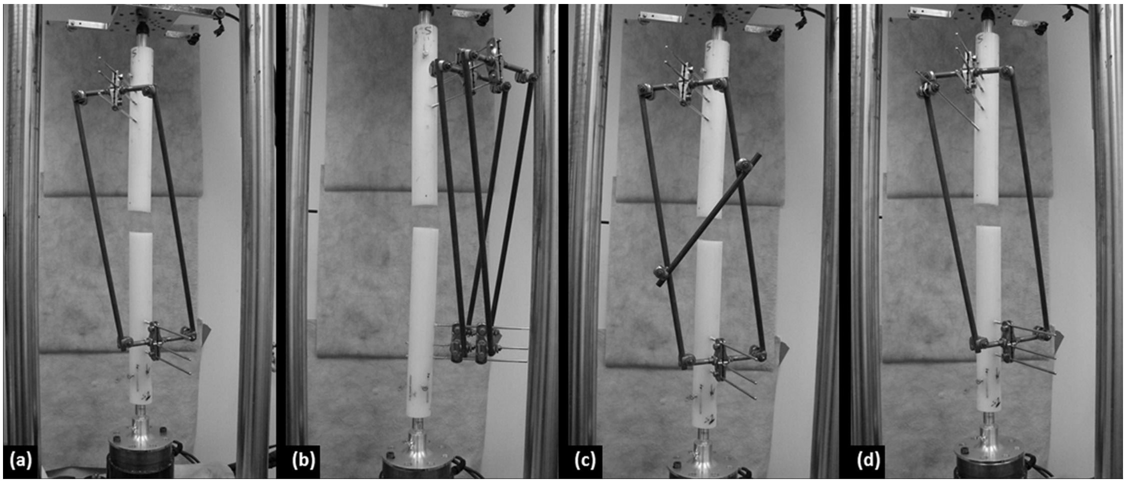

Fig. 1. Configurations of knee-spanning external fixator. (a) standard construct; (b) double-stacked variation; (c) cross-linking; (d) oblique pin variation.

double stacking results in the greatest increase in stiffness but at the greatest increase in cost.

Materials and methods

We modelled the leg in the knee-spanning external fixator using a bone surrogate made of ultra-high-molecular-weight polyethylene pipe (UHMWPE; McMaster-Carr Supply Company, Aurora, OH, USA) with an outer diameter of 5.08 cm and an inner diameter of 2.54 cm. To simulate a comminuted Orthopaedic Trauma Association type C complete tibial plateau fracture, a 3-cm osteotomy site was created within the middle of the bone model to simulate a fracture. The size of the osteotomy also prevented the ends of the bone model from touching during the compression and bending tests.

The "standard" knee-spanning external fixator was based on the configuration that is commonly used at our institution. The dimensions were chosen to simulate those that are typically needed in a clinical setting, leaving room to span the knee joint and an area of the tibia for future fixation (Fig. 1a). All fixators were placed by a single orthopaedic surgeon using a technique identical to that which would be used in the operating room. Based on our experience, failure of the bone-pin interface with a temporary spanning fixator is not a common clinical problem.

All fixators were comprised of Synthes large external fixator components (Synthes, Inc., Paoli, PA, USA). Two clusters of 3 pins each were created with large 6-hole pin clamps, 1 distal and 1 proximal in the model. Five-millimetre self-drilling stainless steel pins were used. The total pin spread between the most proximal and most distal pin within each cluster was 70 mm. The distance between the 2 pin clusters was 450 mm. The distance between the most proximal and the most distal pin in the construct was 590 mm. The carbon fibre rods measured a length of 550 mm and a diameter of 11 mm.

To simulate clinical conditions, the distance between the bone model and the fixator clamps in the tibia was 30 mm, which allowed for the subcutaneous nature of the tibia anteriorly. The distance between the bone model and the fixator clamps in the proximal bone model was 100 mm to allow for soft tissues in the thigh. The pins fully engaged both walls of the bone model. The pin clusters were oriented at a 45-degree angle to each other in the axial plane, to simulate anterior tibial pin and anterolateral femoral pin placement. The construct also consisted of curved outriggers and large combination clamps to hold the carbon fibre rods.

The standard construct was modified to simulate 3 commonly used strategies to increase the stiffness of the frame: double stacking, cross-linking, and use of an oblique pin. For the double stacking variation, a second set of pin-bar clamps and bars was added to the standard external fixator (Fig. 1b). For the cross-linking variation, a cross-link consisting of a 200-mm carbon fibre bar and large combination clamps was added between the 2 550-mm bars (Fig. 1c). For the oblique pin variation, a 5-mm stainless steel pin was added to the construct, extending from the carbon fibre bar to the proximal bone model (Fig. 1d). The additional pin was obliquely inserted at an angle into the proximal pipe, immediately distal to the proximal pin cluster, attached to the most medial carbon fibre rod with a large combination clamp.

Five samples of the standard construct and 5 samples of each of the 3 construct variations were tested in random order. Pilot tests were conducted to determine loading parameters that would ensure loading only in the elastic range of the constructs.

A material testing system (Model 858 Mini Bionix II, MTS Corp., Minneapolis, MN, USA) was used to test 4 different loading modes: anterior–posterior bending, medial–lateral bending, axial compression, and torsion.

Anterior–posterior bending and medial–lateral bending were tested under 3-point bending (Fig. 2) to simulate the forces that occur when the lower limb is elevated clinically or sustains varus or valgus stress. Proximal and distal ends of the bone model were

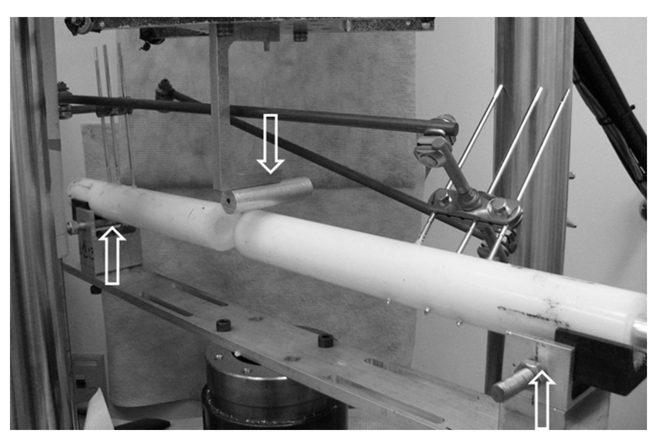

Fig. 2. Specimens were loaded in 3-point bending using custom fixtures to prevent rotations and maintain orientation in anterior–posterior bending and in medial–lateral bending. Loads were applied on the distal pipe in our model.