Biomechanics of Soft-Tissue Interference Screw Fixation for Anterior Cruciate Ligament Reconstruction

Jeff C. Brand, Jr, MD*
David N.M. Caborn, MD†
Darren L. Johnson, MD‡

The quadrupled hamstring may be approximately double the failure strength of the native anterior cruciate ligament (ACL) whereas the bone patella tendon bone (BPTB) plug approximates the native ACL's failure strength. Patients benefit from quadriceps sparing surgical approaches engendered by the harvest of the quadrupled hamstring.¹

Cosmesis² and kneeling pain³ are frequently improved with the quadrupled hamstring. Unfortunately, conventional quadrupled hamstring fixation devices such as suture and post, post and washer, and staples possess poor stiffness and failure loads that are not compatible with a progressive rehabilitation program.⁴ Consequently, effort has been devoted to develop fixation means for the quadrupled hamstring initial strength and stiffness that allow full rehabilitative activities.

Interference fixation of a bone plug was described by Lambert⁵ with a 6.5-mm cancellous screw. In 1987, Kurosaka et al⁶ demonstrated superior strength with a larger diameter screw (9 mm) as an interference fixation positioned against a bone plug. Ten years later, Pinczewski et al⁷ reported posterior cruciate ligament (PCL) reconstruction with a quadrupled hamstring graft fixated with a titanium metal interference screw. Fu⁸ also described quadrupled hamstring grafts secured with a biodegradable interference screw for ACL reconstruction. In 2000, Brand et al⁹ evaluated the biomechanics of a biodegradable interference screw opposed against a quadriceps tendon.

Educational Objectives

As a result of reading this article, physicians will be able to:

1. List the advantages of soft-tissue grafts.
2. Recognize the importance of adequate stiffness and high initial failure strength with biomechanical testing for graft fixation in cruciate ligament reconstruction.
3. Identify the advantages of interference fixation cruciate ligament reconstruction.
4. Define the relationship between bone mineral density and the failure strength of soft-tissue grafts fixated with interference screws placed directly against the graft.
5. Describe measures that are effective in improving failure strength of soft-tissue interference fixation.

As revision ligament surgery becomes more common and multiple ligament surgery improves, the demand for alternative graft choices intensifies. Only the patella tendon offers a bone plug on each end of the graft. The majority of graft choices in ligament surgery are soft-tissue fixated grafts such as quadrupled hamstring, quadriceps tendon, Achilles tendon, anterior tibialis, and posterior tibialis. Although soft-tissue interference fixation is believed to be stiff enough for the demands of rehabilitation, failure loads in biomechanical testing may not be adequate for progressive strengthening and weight-bearing activities.¹⁰

From *Alexandria Orthopaedics and Sports Medicine, Alexandria, Minn; †Louisville, Ky; and the ‡University of Kentucky School of Medicine, Lexington, Ky.

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Reprint requests: Jeff C. Brand, Jr, MD, 1500 Irving, Alexandria, MN 56308.
Patients with soft-tissue grafts should not be denied the benefits of a progressive rehabilitation program accrued by those who have interference fixation with a bone plug. This article reviews the recent science optimizing the biomechanical properties of soft-tissue interference fixation.

**BIOMECHANICAL PROPERTIES**

Although considered the gold standard in ACL reconstruction, the patella tendon strength and stiffness may not be significantly greater than the ACL. The quadrupled hamstring, however, may be almost double the failure strength of the native ACL (Table 1). Soft-tissue grafts, those without bone plugs on each end, may be stronger than the biomechanical data suggest. Grip failures or slippage of soft-tissue grafts in the testing devices are common given the high level of applied force. If grip fixation is improved, the failure load may be higher for the soft-tissue grafts. For example, the quadriceps tendon has a large cross-sectional area, yet a relatively low ultimate failure given its large cross-sectional area. The large cross-sectional area and short length of the quadriceps tendon does not allow immobilization of independent tendon fibers in present cryogrip systems.

**INTERFERENCE FIXATION**

Interference fixation of a BPTB graft provides the strength and stiffness required for activities of daily living and a progressive rehabilitation program, making it the gold standard of graft fixation.15

**Soft-Tissue Grafts**

Due to the success and advantages of large diameter screw interference fixation directly against a BPTB, the technique of an interference screw placed directly against a graft was adapted to soft-tissue grafts.7,8 Graft fixation stiffness improves with a metal or biodegradable interference screw positioned against a soft-tissue graft compared to an EndoButton (Smith & Nephew, Hamburg, Germany) with a closed loop or a hamstring linked with a suture to a post10,17 (Table 2). Unfortunately, biomechanical testing of soft-tissue grafts fixated with an interference screw revealed poor failure loads that have been lower than conventional hamstring fixation methods (Table 2).

Knee motion, gait training, and muscle strengthening during rehabilitation load relax the graft in a cyclic fashion. Cyclic loads that duplicate the rehabilitative stresses applied to the graft fixation complex have been poorly tolerated by an interference screw fixated with soft-tissue grafts. In some studies, soft-tissue grafts fixated with interference screws have resulted in catastrophic failure as the cyclic loads are applied.9,22

Graft fixation with high initial failure strength resists cyclic loading better than grafts with lower initial failure strength.23 Restricting cyclic loading with conservative rehabilitation programs has been attempted previously with soft-tissue graft fixation. Most knee surgeons advocate progressive rehabilitation programs to promote early knee function and improve patient outlook. Research of soft-tissue interference fixation focuses on improved load at failure to allow for cyclic loading that occurs with rehabilitation.

**Biology**

Soft-tissue tendon grafts fixated outside the bone tunnel or extra-articularly in animal models demonstrate a fibrous interface at all time points between the soft-tissue graft and bone tunnel.24,26 It is essential to understand tendon to bone healing progression with interference screw fixation. In an animal model, Weiler et al17 found healing progresses only partially via the development of a so-called fibrous interface as previously described for extra-articular

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**TABLE 1**

<table>
<thead>
<tr>
<th>Craft Selection</th>
<th>Ultimate Strength of Failure (N)</th>
<th>Stiffness (N/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Native ACL</td>
<td>2160</td>
<td>242</td>
</tr>
<tr>
<td>Patella tendon</td>
<td>2977</td>
<td>455</td>
</tr>
<tr>
<td>Quadrupledhamstrings (Semitendinosus and gracilis)13</td>
<td>4140</td>
<td>807</td>
</tr>
<tr>
<td>Quadriceps tendon14</td>
<td>2353</td>
<td>326</td>
</tr>
<tr>
<td>Loop of anterior tibialis15</td>
<td>4122</td>
<td>625</td>
</tr>
<tr>
<td>Loop of posterior tibialis15</td>
<td>3594</td>
<td>511</td>
</tr>
</tbody>
</table>

Abbreviation: ACL=anterior cruciate ligament.

**TABLE 2**

<table>
<thead>
<tr>
<th>Study</th>
<th>Failure (N)</th>
<th>Stiffness (N/mm)</th>
<th>Failure Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brown et al9,10</td>
<td>214±78.8</td>
<td>8.98±6.69</td>
<td>Tendons pulled out or slipped</td>
</tr>
<tr>
<td>Magen et al17,19</td>
<td>350±134</td>
<td>340±84</td>
<td>Not reported</td>
</tr>
<tr>
<td>Weiler et al10</td>
<td>201±50.6</td>
<td>36.2*</td>
<td>Failed at the tibial socket</td>
</tr>
<tr>
<td>Caborn et al11,16</td>
<td>242±90.7</td>
<td>None reported†</td>
<td>Failed by graft slipping</td>
</tr>
<tr>
<td>Caborn et al17,18</td>
<td>341±162.9</td>
<td>None reported†</td>
<td>Graft slipped</td>
</tr>
</tbody>
</table>

*Quadrupled semitendinosus/gracilis interference screw with the RCI titanium screw.
†Standard deviation not reported.
‡Quadrupled semitendinosus/gracilis interference screw with Bioscrew.
TABLE 3
Effect of Bone Mineral Density on Ultimate Failure Strength of a Biodegradable Interference Screw Fixation of a Quadrupled Hamstring Tendon Graft*

<table>
<thead>
<tr>
<th>Biodegradable Screw 0.5-mm Tunnel Sizing</th>
<th>Tibia (N)</th>
<th>Femur (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMD &lt;0.6 on the tibia (n=6)</td>
<td>216 (44-525)</td>
<td>427 (253-515)</td>
</tr>
<tr>
<td>BMD &gt;0.6 on the tibia (n=3)</td>
<td>495 (420-621)</td>
<td>737 (583-853)</td>
</tr>
</tbody>
</table>

Abbreviation: BMD=bone mineral density. *Represented as mean (range).

soft-tissue fixation. Extensive investigation in a sheep model with a biodegradable interference screw fixation of an Achilles tendon graft demonstrated direct contact healing between the graft and bone surface if compression or interference fixation is used.27

VARIABLES OF FIXATION

In an effort to improve ultimate load at failure of soft-tissue interference fixated grafts, several variables have been identified and evaluated. Bone mineral density, screw material, tunnel sizing, tunnel impaction, screw geometry, and cyclic loading all impact the fixation formula.

Bone Mineral Density

Soft-tissue interference fixation relies on the biomechanical properties of cancellous bone to serve as a fixation substrate.10 The biomechanical properties of bone can be assessed with quantitative computed tomography or dual photon absorptiometry. Dual photon absorptiometry offers an accurate, reliable indication of metaphyseal bone and has been used in biomechanical investigations. Excellent side-to-side agreement in 20 pairs of cadaver knees verified that dual photon absorptiometry is a reliable assessment of bone mineral density.29

Patients similarly aged to the cadaver specimens measured at the University of Kentucky Biomechanics Laboratory demonstrated comparable bone mineral density values when evaluated in the same area of the tibia.29

Dual photon absorptiometry of the tibial metaphysis is less than the femoral metaphysis bone mineral density in the same knee of elderly cadaveres.28,29 and young females.30 The lower tibial bone mineral density may explain lower failure loads experienced by tibial soft-tissue interference fixation.

The relationship between failure load of soft-tissue interference screw fixation and bone mineral density relies on the screw material. Screw material may be biodegradable or metal.

Biodegradable Interference Screws.

In our laboratory, quadrupled hamstring grafts fixated with biodegradable interference screws and sized within 0.5-mm bone tunnels were found to rely on the bone mineral density of the host bone. The variables of insertion torque and bone mineral density explain 77% of the maximum load observed (P<.0001) for the quadrupled hamstring tendon grafts secured in bone tunnels. The R2 value for the relationship between bone mineral density and ultimate load at failure was 0.65, therefore, bone mineral density explains 65% of the ultimate load at failure.29

The relationship of bone mineral density to ultimate load at failure in the BPTB and quadriceps tendon model fixated by a biodegradable interference screw also was evaluated. The R2 correlation coefficient (0.65) of the quadriceps tendon graft was nearly identical to that of a quadrupled hamstring with bone tunnels sized within 0.5 mm of the graft diameter. Also, the BPTB ultimate failure load was determined by bone mineral density. The coefficient of correlation was 0.71, which indicates that 71% of the ultimate load at failure was determined by the bone mineral density of the metaphyseal bone.9

If the "fit" between the quadrupled hamstring graft diameter and bone tunnel is within 1 mm instead of 0.5 mm, the R2 decreases to 0.44. As the tunnel fits closer to the graft, bone mineral density determines ultimate load at failure to a greater extent.29

Bone mineral density of 0.6 gm/cm2 ensures improved interference fixation strength of a soft-tissue graft with a biodegradable screw. Tibial and femoral fixation strength significantly improves if metaphyseal bone mineral density is ≥0.6 gm/cm2 (Table 3).29

A cyclic loading test of the quadriceps tendon found that 6 of 10 constructs survived 1000 cycles. All 4 cycling failures were in femurs and tibias that had poor (<0.6 gm/cm2) bone mineral density. In a given knee, if the femoral bone mineral density was >0.6 gm/cm2, catastrophic failure did not occur with cycling in this study.9

Metal Interference Screw. Metal interference screw fixated quadrupled hamstring tendon grafts ultimate load at failure is not as dependent on bone mineral density as the biodegradable screw fixated quadrupled hamstring tendon graft. Grafts fixated in bone tunnels sized within 0.5 mm of the graft diameter possessed a correlation coefficient of R2=0.20. At this time, this observation is not explained by biomechanical parameters measured. Based on this data, quadrupled hamstring fixed with a metal interference screw in bones with diminished bone mineral density may improve fixation strength.

Clinical Implications. As patients age, the bone mineral density of the femoral and tibial metaphyses diminishes.29 Suspected bone mineral density of patients in their 60s approximates 0.65 gm/cm2 (Table 4). Anterior cruciate ligament reconstruction, traditionally performed in younger patients, is made available to middle-aged and older patients; in one report, a patient
was 84 years old. At this time, soft-tissue grafts fixed with biodegradable interference screws do not provide adequate initial loads at failure or durable cyclic characteristics, due to poor bone mineral density, to permit an aggressive rehabilitation program for patients in their 60s.

**Screw Material**

A biodegradable interference screw offers several advantages compared to a metal interference screw. Magnetic resonance imaging is not degraded by artifact from the metal interference screw. Cost savings can be realized if the implanted device does not have to be removed. Revision and secondary procedures, such as high tibial osteotomy, are simplified by the drill-through capabilities of biodegradable implants.

Two investigations have compared a biodegradable interference screw to a metal interference screw in soft-tissue graft interference fixation. Both investigations used a similar number of cadavers with similar bone mineral density in a paired, elderly, human cadaver study. The first, published in 1999, noted a slight, insignificant improvement in fixation strength at failure with a biodegradable screw compared to a metal screw in bone tunnels sized within 1 mm of quadrupled hamstring diameter. The second investigation, presented in 2001, found a significant improvement in femoral fixation with a biodegradable screw compared to a metal interference screw when the bone tunnels were within 0.5 mm of quadrupled hamstring diameter (Figure 1). The soft-tissue grafts sustained greater and more extensive damage than the metal screw group in the second investigation. Damage occurred in 9 of 10 grafts in the metal screw group and 1 of 10 grafts in the biodegradable screw group (Figure 2).

**Tunnel Diameter**

The fit of the soft-tissue graft in the bone tunnel proved to be an important factor in the fixation formula. A quadrupled hamstring fixed with a biodegradable interference screw possesses a higher load at failure if the bone tunnel is sized within 0.5 mm of the graft diameter compared to a quadrupled hamstring secured with a biodegradable interference screw in a bone tunnel sized within 1 mm of the quadrupled hamstring diameter. The improvement in femoral fixation was significant, 530 N compared to 341 N (P < .05). Tibial fixation, although increased in bone tunnels sized within 0.5 mm of the quadrupled hamstring, the difference, 308 N versus 222 N, was not significant.

**Tunnel Impaction**

The quadrupled hamstring tendon graft fixated with biodegradable interference screws (Arthrex, Naples, Fla) in bone tunnels and the role of tunnel impaction has been investigated. Drilling an undersized tunnel and serially dilating the bone tunnel for a precise fit to the quadrupled hamstring increased the load at failure 70% compared with grafts not fixed in impacted bone tunnels. Biologic transosseous integration has not been evaluated or compared with grafts in which the bone tunnel is not impacted.

**Screw Geometry**

By increasing the screw length and screw diameter, fixation strength is significantly improved. In a biomechanical study of screw geometry, the influence of screw length (23 mm versus 28 mm) was greater than that of thread diameter (screw diameter=graft size versus screw diameter=graft size + 1 mm). A biomechanical investigation in young, human cadaver tibia evaluated a quadrupled hamstring tendon graft construct secured with either a 28- or 35-mm screw in the tibial tunnel that was impacted to within 0.5 mm of graft size from 2 mm less than graft size. The difference between the 28-mm and 35-mm screw means maximal load at failure and stiffness was significant (Table 5).

From the same laboratory using the same methodology, further comparison to two tibial screws positioned in series, one placed as aperture fixation and one placed as cortical fixation, was

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### Table 1

<table>
<thead>
<tr>
<th>Comparison of the Mean Metaphysial Bone Mineral Density of Aged Cadavers</th>
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<tbody>
<tr>
<td>Between Groups</td>
</tr>
<tr>
<td>Brand et al²⁵</td>
</tr>
<tr>
<td>Madsen et al²¹*</td>
</tr>
<tr>
<td>Madsen et al²¹*†</td>
</tr>
<tr>
<td>Vouri et al²⁵*‡</td>
</tr>
</tbody>
</table>

*Bone mineral density was measured in the metaphyseal area of elderly patients.
*Data were obtained from young, healthy female patients whose bone mineral density was measured in a similar fashion.

**Figure 1:** Comparison of ultimate load at failure between a quadrupled hamstring tendon graft fixed in a bone tunnel, templated within 0.5 mm, with a biodegradable interference screw and a metal interference screw.

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tested. The single 35-mm interference biodegradable screw demonstrated a superior load at failure, although not statistically significant, when compared to the two tibial interference screws placed in series (Table 5).37

Cyclic Loading

Rehabilitative loads may be replicated in the laboratory by application of repetitive or cyclic loading. In elderly human cadavers, the bone plug of a BPTB was compared to the soft-tissue end of a quadriceps tendon graft secured with a biodegradable interference screw directly against the bone plug. Among all groups tested no significant difference was noted in load to failure between the soft-tissue quadriceps tendon graft and a bone plug graft after 20 or 1000 cycles. In this study, cyclic loading did not adversely affect the ultimate load at failure of the bone plug or the soft-tissue construct.

Femoral tunnel quadriceps tendon interference fixation with a biodegradable interference screw was comparable to femoral tunnel BPTB interference fixation in stiffness, displacement to failure, and ultimate failure, both with 20 and 1000 cycles. Tibial tunnel interference fixation with a BPTB or quadriceps tendon was comparable after the constructs had been cycled for 1000 repetitions; however, the BPTB possessed superior stiffness after 20 cycles compared to the soft-tissue quadriceps tendon graft.9

The EndoButton, linked to the soft-tissue quadriceps tendon graft with Dacron tape woven through the quadriceps tendon, had significantly more displacement at failure and less stiffness than quadriceps tendon biodegradable interference screw femoral fixation at time zero. Currently, the EndoButton linked with Dacron tape to the soft-tissue quadriceps tendon graft cannot be recommended for femoral fixation due to its poor stiffness and high elongation at failure (Table 6).9

Interference screw fixed grafts undergoing 1000 cycles significantly improved the displacement at failure and stiffness compared to 20 cycles in all groups except the femoral BPTB fixation construct. Stiffness is the slope of the linear region of the load-elongation curve and usually is reported in units such as Newtons/millimeter (N/mm). As a graft and its fixation device are loaded with a tensile force, displacement in the graft and fixation device occurs. Repetitive loading removes creep from the graft fixation construct. Decreasing creep in the fixation construct lessens displacement at failure, which improves stiffness. Displacement of the graft at failure is the denominator of stiffness, suggesting that further cycling in the operating room beyond 20 cycles of the graft and interference screw fixation would improve the biomechanical characteristics of stiffness and displacement of the graft to failure.9 As stiffness increases, the graft resists cyclic loading. Improved resistance to cyclic loading results in a more stable knee.

ADJUNCTS TO FIXATION

Combining fixation devices (ie, the use of hybrid fixation techniques) may improve the stiffness and ultimate tensile load bearing abilities of soft-tissue interference fixation. Low loads at failure in biomechanical testing and paucity of clinical studies force advocates of soft-tissue interference fixation to use adjunctive fixation adjacent to or in series with the soft-tissue interference screw.

Femoral Fixation

Endobutton. Direct biomechanical comparison between EndoButton linked with a closed loop or endotape revealed
similar stiffness data, but a much higher ultimate tensile testing was demonstrated with the closed loop (1345 N versus 644 N) for the endo-tape linked EndoButton.\(^3\) Biomechanically, the EndoButton linked with tape has motion of the graft in the tunnel of up to 3 mm, creating shear forces under physiologic cyclic loads.\(^3\) This longitudinal motion or “bungee” effect has been associated with tunnel expansion in clinical trials.\(^4\)

Endopearl. The EndoPearl (Linvatec, Largo, Fla) significantly improves fixation with a biodegradable interference screw over the load at failure without the EndoPearl. The EndoPearl consists of a small biodegradable sphere linked with suture to the looped end of the quadrupled hamstring (Figure 3). Once the graft and Endopearl have been passed, a biodegradable interference screw secures the graft, with the Endopearl resting at the tip of the biodegradable interference screw (Figure 4).

Weiler et al\(^2\) compared the EndoPearl combined with a biodegradable interference screw to a quadrupled hamstring graft fixed with only a biodegradable interference screw in young calf bone with bone mineral density matched to that of young human femurs. Use of an EndoPearl significantly improved ultimate load at failure and stiffness and diminished the standard deviation of each parameter, indicating more consistent load bearing properties\(^3\) (Table 7). The EndoPearl group survived significantly more cycles at failure than the group fixed with a biodegradable interference screw alone, 388.5 compared to 152.8.\(^2\)

**Tibial Fixation**

Screws Used as a Post. A metal bone screw can be used with a standard metal washer as a post to tie suture around, or it can be used with a soft-tissue washer against tendon as back up for tibial interference fixation. A screw with a soft-tissue washer placed directly against quadrupled tendon graft is slightly stronger and stiffer than the screw used as a post with suture.\(^6\) A screw with a soft-tissue washer is preferable to tibial soft-tissue fixation with a post linked with suture because it avoids the more elastic suture thereby improving stiffness.

Endotack. The Endotack (Karl Storz GmbH & Co KG, Tuttingen, Germany) is a self-tightening, low profile metal device designed for cortical fixation at the cortical opening of the tibial tunnel. The free suture ends of the quadrupled hamstring tendon graft pass through the holes of the button-like device. A tightening device applies the Endotack to the cortical opening of the tibial tunnel. Because a second transplant cortical drill hole is not required, the tibial artery and nerve are not endangered. The Endotack, although designed as sole tibial fixation for a quadrupled hamstring tendon graft, also provides adjunctive fixation to a soft-tissue interference screw.

Interference Screws in Series (Bicor-\(\text{tical Screws}). Additional fixation provided by a second biodegradable interference screw positioned as cortical fixation also serves as adjunctive fixation. However, fixation with two biodegradable interference screws proved inferior to a single 35-mm biodegradable interference screw in biomechanical testing\(^3\) (Table 5).

**Clinical Experience**

At least three clinical investigations of quadrupled hamstring interference fixation support this technique in select patients. Allen et al\(^1\) evaluated 30 patients an average 15 months postoperatively. The authors concluded this technique “is a viable procedure for reconstruction of the ACL-deficient knee.”

Musgrove et al\(^1\) developed a reverse thread metal interference screw that positions the graft posterior in the femoral tunnel, hence improving isometry of the graft for right knees of male patients. Mean reported follow-up was 12 months. Significant improvement in
improved knee stability in a biomechanical study with BPTB grafts. Compressive fixation of soft-tissue grafts may allow for direct bone apposition to the soft-tissue grafts without an interposed fibrous interface. As biomechanical properties of soft-tissue fixation such as stiffness and load at failure improve, graft laxity post reconstruction should match that of BPTB autografts fixed with interference screws.

At this time, soft-tissue grafts fixed with biodegradable interference screws do not provide adequate initial loads at failure or durable cyclic characteristics to permit a progressive rehabilitation program in patients in their 60s because of diminished bone mineral density. Therefore, patients suspected of poor bone mineral density, <0.6 gm/cm², would be better served with periosteal fixation of multiple stranded hamstring grafts.

Grafts sized within 0.5 mm of the bone tunnel diameter, tunnel impaction, and screws of longer lengths all improved load at failure of soft-tissue grafts fixed with an interference screw. Biodegradable interference screws perform comparably or better than metal interference screws in biomechanical testing at time zero. Substitution of a biodegradable interference screw for a metal interference screw (which has been clinically evaluated) against a soft-tissue graft should prove efficacious. Further cycling in the operating room beyond 20 cycles of the graft and graft fixation improves the biomechanical characteristics of stiffness and displacement of the graft at load to failure.

In addition to previously reported problems of biodegradable screws including screw breakage and incomplete degradation, we report an instance of screw displacement without loss of knee stability. Adjuncts to interference screw fixation improve failure loads of soft-tissue fixation. Clinical trials with metal interference screws demonstrate stable knees in young, male patients. Further work in soft-tissue fixation will define suitable patient populations for this technique.

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