The Biomechanical Effect of a Lateral Meniscus Posterior Root Tear With and Without Damage to the Meniscofemoral Ligament: Efficacy of Different Repair Techniques

Philipp Forkel, M.D., Mirco Herbort, M.D., Frederike Sprenker, Cand. Med., Sebastian Metzlaff, M.D., Michael Raschke, Ph.D., and Wolf Petersen, Ph.D.

Purpose: To evaluate the effect of the meniscofemoral ligament (MFL) in maintaining lateral-compartment contact pressures after injury to the posterior root of the lateral meniscus, and to measure the ability to restore intra-articular loads to normal by repairing the posterior root to the tibia after transection of the posterior root and the MFL. Methods: Ten human cadaveric knee joints were axially loaded to 100 N. A digital pressure sensor measured the contact pressure in the lateral compartment. Five different conditions were tested: intact, after release of the posterior root of the lateral meniscus, after transection of the MFL along with release of the posterior root, refixation of the posterior root of the lateral meniscus to the tibia using an anatomic transosseous tunnel, and refixation of the root of the lateral meniscus using a tibial anterior cruciate ligament (ACL) tunnel. Results: After transection of the posterior lateral meniscus root, the contact pressure did not increase significantly. The additional transection of the MFL led to a significant increase in the contact pressure. Anatomic fixation of the meniscus posterior horn reduced the femorotibial pressure to nearly pre-sectioning values. The reattachment of the meniscus posterior horn through a tibial ACL tunnel was equivalent to an anatomic fixation. Conclusions: In the case of a root tear of the lateral meniscus, the MFL maintains meniscus function and stabilizes the pressure in the lateral compartment. A complete detachment of the posterior meniscus horn (MFL and root tear) leads to an increase in the intra-articular pressure. A root repair normalizes the pressure down to normal values. The tibial ACL tunnel is suitable to perform the repair and to lead out the suture. Clinical Relevance: In the case of a complete detachment of the meniscus posterior horn, fixation of the posterior root is necessary to restore the meniscus function and to guarantee an equal pressure distribution in the lateral compartment. It can be combined with an ACL reconstruction.

The knee joint menisci increase femorotibial congruence, and they contribute significantly to load transmission and joint stability. During load transmission, the forces acting on the meniscus are transformed into circumferential hoop stress. This circular hoop stress is transmitted to the tibial plateau by the anterior and posterior roots of the menisci. Therefore the posterior horn attachments of the menisci are essential in maintaining the mechanical function of the menisci. The anatomy of the lateral meniscus posterior attachment differs from the anatomy of the medial meniscus. In addition to the tibial attachments, the posterior horn of the lateral meniscus is connected to the intercondylar area of the femur by the meniscofemoral ligaments (MFLs). The MFLs show a high variation of the femoral insertion site. The Wrisberg ligament (posterior MFL) and the Humphrey ligament (anterior MFL) typically insert at the medial femoral condyle. An attachment to the PCL is also common. The posterior MFL is difficult to assess arthroscopically, although we know of its high prevalence of up to 69% from cadaveric studies. The function of the MFL as a secondary restraint to posterior drawer is well known. Amadi et al. showed that a single transection of the MFL leads to an increase in the intra-articular pressure. However, the capability of the MFL to prevent the loss of meniscus function in the case of a root tear is debated controversially and...
has not been tested in a human cadaveric model previously. Schillhammer et al. showed the effectiveness of transosseous fixation of the lateral meniscus horn in the case of a root tear in a biomechanical study. In the case of a root tear and an anterior cruciate ligament (ACL) injury, the surgeon has to deal with 2 injuries and has to decide whether fixation of the meniscus is necessary and whether a combination of fixation of the meniscus and ACL reconstruction as described by Forkel and Petersen can be performed. However, the biomechanical effectiveness of this technique has not been tested.

The first aim of this study was to evaluate the effect of the MFLs in maintaining lateral-compartment contact pressures after injury to the posterior root of the lateral meniscus. The second aim was to measure the ability to restore intra-articular loads to normal by repairing the posterior root to the tibia after transection of the posterior root and the MFL. Two different tibial tunnel positions were compared.

We hypothesized that the tibiofemoral contact pressure does not increase in the case of an isolated root tear of the posterior lateral meniscus. An additional cut of the MFL leads to a significant increase in the tibiofemoral pressure. The second hypothesis was that fixation of the posterior meniscus horn through an ACL tunnel can restore the meniscus function of stabilizing the intra-articular pressure.

**Methods**

Ten cadaveric human knee joints were used to measure the intra-articular pressure in the lateral compartment. The mean age of the body donors was 68.7 years (range, 61 to 79 years). The knee joints were fresh frozen and stored at −20°C. The knees were thawed at room temperature for 24 hours before testing. The exclusion criteria were grade 4 osteoarthritis in the lateral joint space and a torn lateral meniscus. On the basis of these criteria, 2 knees had to be excluded. Most knees showed grade 2 to 3 osteoarthritis. This was visible by the anterior approach. Therefore radiographs or arthroscopic inspections were not necessary before testing.

Five different conditions of the lateral meniscus root were tested: (1) intact lateral meniscus, (2) root tear of the lateral meniscus (Fig 1A), (3) lateral meniscus root tear and additional transection of the MFL (Fig 1B), (4) anatomic transtibial fixation of the lateral meniscus horn in the center of the root attachment (Fig 2), and (5) transtibial fixation through an ACL tunnel in the center of the tibial ACL attachment (Fig 3).

A digital pressure sensor (st Sensor Type S2042; Novel, Munich, Germany) was placed in the lateral joint space between the femur and the meniscotibial surface, and an axial load was applied to the knee using a material testing machine according to the testing protocol used in porcine knee models as described in previous studies (Fig 4).

The sensing area was 28 × 45 mm², including 194 sensors, with a typical pressure range of 50 kPa up to 2,000 kPa. The sensor covered about 80% of the lateral tibial plateau and did not need to be removed during the first 3 testing conditions. To fixate the root, the sensor had to be removed from the joint and had to be reinserted again in the same place in the lateral compartment. The correct position after reinsertion of the sensor was controlled visually. The reference was the anterior horn of the lateral meniscus.

To apply the axial load on the knee, a material testing machine (Z005; Zwick/Roell, Ulm, Germany) was used. The tibia of the knee joint was embedded in a
custom-made device using a 2-component polyurethane plastic (Technovit 3040; Heraeus Kulzer, Wehrheim, Germany) (Fig 4). The proximal femur was denuded from muscles and soft tissues and fixed in a clamp, and the whole construct was mounted on the testing machine. The axial load was applied at extension with a standardized angle of 0°. The joint line of all knees was positioned at a 90° angle to the load axis so that an existing valgus or varus deviation of the specimens could be neglected.

We used a 20-N/s loading rate because of the accuracy of the sensor and, furthermore, to control the loading mechanism, not to exceed the maximum applied load limit (2,000 kPa) of the sensor. The material testing machine applied a maximum axial load of 100 N. Initially, a preload of 1 N was applied to the specimens. All tests were based on the same loading protocol. Peak pressure, mean pressure, and the pressure in a defined region of interest (ROI) around the peak pressure spot were documented. Furthermore, the difference in pressure between peak contact pressure and mean pressure was calculated. The area of interest was defined as the 1-cm² area around the peak contact pressure. This area corresponds to 16 pressure-measuring squares.

The forces were recorded for the different conditions according to the described loading protocol. First, the intact state of the lateral meniscus was tested. Without removing the sensor, we transected the lateral meniscus posterior root with a scalpel through a posterior approach. The forces were measured for the isolated lateral meniscus tear and for the transected meniscofemoral attachments.

Two different transosseous fixation techniques were then tested. To guarantee the same intra-articular conditions, 2 tunnels with a diameter of 4.5 mm were drilled: (1) at the center of the posterior meniscus root at the tibia and (2) at the center of the tibial attachment of the ACL (Figs 2 and 3).

The root was sutured with a single loop of a No. 2-0 braided polyester suture. First, fixation through the anatomic tunnel at the root was performed, and the meniscus was reduced to the tibia. The suture was knotted over a flip button (Flip Tack; Karl Storz, Tuttingen, Germany) (Fig 2). Then, the knot was untightened, and the suture was led out through the tunnel in the center of the tibial ACL attachment anterior to the first tunnel. The meniscus was reduced to the tibia, and the suture was knotted over the flip button (Fig 3).

Quantitative values were presented as mean and standard deviation, minimum and maximum, and quartiles. They were tested for normal distribution by use of the Shapiro-Wilk test. Because of significant deviations from normal distribution, the evaluated dependent samples (peak pressure, mean pressure, and pressure in a defined ROI) were compared by the Friedman test. Pairwise post hoc tests were performed.
in case of a significant global effect using the Schaich-Hamerle test.

Ordinaly or nominally scaled values were displayed as absolute and percent frequencies. The primary endpoint for post hoc power analysis was the peak pressure in the lateral compartment.

The tests were double sided with a significance level of 5%. An α adjustment for multiple testing was not applied, and the results were interpreted accordingly. Statistical calculations were performed with SPSS Statistics software, version 21 (SPSS, Chicago, IL).

Results

Mean Joint Contact Pressure

For the intact lateral meniscus, the mean pressure was 144.59 ± 23.88 kPa. After creation of a standardized root avulsion, the mean pressure in the lateral compartment did not increase significantly (P = .417) (Figs 5A, B, and 6 and Table 1).

In the case of a standardized root tear and an additional transection of the MFL, the mean pressure in the lateral compartment increased significantly compared with the intact state of the lateral meniscus (P < .001) (Figs 5C and 6 and Table 1).

The anatomic reduction of the lateral meniscus posterior horn to the tibial attachment resulted in a decrease in the mean pressure in the lateral compartment down to normal pre-sectioning values. This decrease was significant compared with complete posterior detachment of the meniscus (P = .002). There was no significant difference compared with the intact state (P = .471).

Comparison of anatomic fixation versus fixation through the tibial ACL tunnel showed no significant difference of the 2 techniques concerning mean pressure (P = .736). Comparison of ACL tunnel fixation with the intact state showed no significant difference (P = .417) (Figs 5D, E, and 6 and Table 1).

Peak Pressure

For the intact state, the peak pressure measured in the lateral compartment was 440 ± 87.94 kPa. The root tear of the lateral meniscus led to a slight increase in the

Fig 6. Box-plot diagram of mean pressure in lateral compartment. (anat, anatomic; refix, refixation.)
peak pressure, but the increase was not significant ($P = .836$). The combination of a root tear and a tear of the MFL resulted in a significant increase in the peak pressure ($P = .001$). Anatomic fixation and reduction of the root through the tibial ACL tunnel were equal in reducing the intra-articular pressure ($P = .836$) (Figs 5 and 7 and Table 2).

**Mean Pressure in ROI**

In a defined ROI around the peak pressure spot, the mean pressure was calculated. These measurements showed similar results to the calculated mean pressure and the peak pressure in the lateral compartment. There was no significant increase in the calculated pressure in the case of a root tear compared with the intact state ($P = .092$). The root tear and additional transection of the MFL increased the intra-articular pressure up to about 4-fold higher values ($P < .001$). Anatomic fixation and reduction of the root through the tibial ACL tunnel resulted in a significant decrease in the contact pressure down to normal levels ($P = .009$). There was no significant difference between these 2 fixation techniques ($P > .999$) (Fig 8 and Table 3).

**Calculated Difference Between Peak Pressure and Pressure in ROI**

The calculated difference between the peak pressure and the mean pressure in a defined ROI around the peak pressure spot was 231 to 443 kPa (212 kPa) for the intact state. In the case of a root tear, the difference was 237 kPa. Cutting the root and the MFL resulted in a calculated difference of 586 kPa. Anatomic fixation and ACL tunnel fixation reduced the values to a normal level (252 kPa and 226 kPa, respectively). These calculated values show the concentration of the pressure distribution on a smaller area in the case of a lateral root tear and transection of the MFL. After reduction of the meniscus, the pressure distribution was equal to the intact state.

**Statistics**

The Friedman test showed significant differences between each property. Because the Schaich-Hamerle test showed significant global effects (peak pressure, mean pressure, and pressure in a defined ROI), a pairwise post hoc test was performed. The primary endpoint was the peak pressure in the lateral compartment. The power efficiency of the Friedman 2-way analysis of variance by ranks (relative to the single-factor within-subjects analysis of variance) was as follows: $0.995 \times \frac{5}{6} = 0.829$. This led to a resulting power of 0.83.

**Discussion**

The most important finding of our study was the stabilizing effect of the MFL in the case of an isolated root tear. The results further prove the assumption that transection of the posterior root of the lateral meniscus and additional transection of the MFL result in a significant increase in the contact pressure. The 2 fixation techniques restore the pressure distribution at the tibial plateau. The posterior root tear of the lateral meniscus—in contrast to the medial meniscus—is a result of a traumatic injury.\(^{12,13}\) The posterior lateral meniscus root tear is a common concomitant injury of an ACL rupture.\(^{12,13}\) In a series of 559 knee magnetic resonance imaging studies with arthroscopic correlation, De Smet et al.\(^{13}\) reported an overall incidence of 2.9% for posterior lateral meniscus root tears. In patients with ACL tears, the incidence was 10-fold higher compared with patients without ACL tears (8% and 0.8%, respectively).\(^{13}\) Brody et al.\(^{12}\) reported an incidence of posterior lateral root tears of 9.8% in 264 patients with ACL tears. The combination of an ACL rupture, lateral meniscus root tear, bone bruise at the

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**Table 1. Mean Pressure in Lateral Compartment**

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>SD</th>
<th>Minimum</th>
<th>Maximum</th>
<th>25th Percentile</th>
<th>50th Percentile (Median)</th>
<th>75th Percentile</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Root tear</td>
<td>167.04</td>
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<td>205.21</td>
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<td>163.465</td>
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<td>331.043</td>
<td>237.2888</td>
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<td>227.99</td>
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<td>Anatomic fixation</td>
<td>157.747</td>
<td>23.3479</td>
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<td>205.1</td>
<td>141.335</td>
<td>154.69</td>
<td>170.2875</td>
</tr>
<tr>
<td>Fixation through ACL tunnel</td>
<td>177.768</td>
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<td>136.39</td>
<td>273.33</td>
<td>149.9025</td>
<td>172.08</td>
<td>184.935</td>
</tr>
</tbody>
</table>

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**Fig 7.** Box-plot diagram of peak pressure in lateral compartment. (anat, anatomic; refix, refixation.)
lateral femoral condyle, and posterior impression fracture at the tibia is a common finding, and it was described as the “lateral quartet.”

In a preliminary study investigating the influence of a root tear and the combination of a root tear and a cut of the MFL on the pressure distribution in the lateral compartment in the porcine knee, we found a significant increase in the pressure in the case of a complete posterior detachment of the lateral meniscus. There was no significant difference in mean contact pressure between the state with the menisci intact and an isolated posterior root tear of the lateral meniscus. In a recent finite-element study published by Bao et al., the influence of an intact MFL in the case of a root tear was tested. They found that a complete radial posterior lateral meniscus root tear is not functionally equivalent to total meniscectomy. They concluded that the torn posterior root of the lateral meniscus continues to provide some load transmission and distribution functions across the joint. They further hypothesized that the posterior MFL prevents excessive radial displacement of the lateral meniscus despite a root tear and assists in transmitting a certain amount of stress in the lateral compartment. These findings are comparable with our results.

Schillhammer et al. also investigated the effect of a lateral meniscus root tear. Lateral-compartment contact pressures were measured by a sensor on the tibial plateau in 8 cadaveric knees with the knee intact, after sectioning the posterior horn of the lateral meniscus to simulate posterior horn detachment, and after repairing the injury. A repair was performed using an ACL tunnel guide to drill a tunnel from the anteromedial tibia to the posterior horn attachment site. Dynamic pressure data were continuously collected by a conductive ink pressure sensing system while each knee was moved through a physiological gait flexion cycle. The authors found a significant increase in tibiofemoral contact pressure in the case of a complete posterior detachment of the meniscus. However, in their study the isolated cut of the posterior root was not compared with a complete transection of the posterior meniscus horn as we did. The isolated injury of the posterior root with an intact MFL is more frequent in clinical practice than the combined injury.

The described anatomic pullout fixation technique in the study by Schillhammer et al. is similar to the first fixation technique tested in our study. The results of an equal pressure distribution after root repair are comparable with our findings.

“Root tears” of the menisci are defined as avulsion injuries of the meniscal attachments to the tibial plateau or radial tears occurring within 1 cm of the bony insertion. The presented data of this study maintain the necessity of a closer look concerning the integrity of the MFL.

The results of our study confirm clinical observations. Shelbourne et al. evaluated the outcomes of 33 patients with posterior lateral meniscal root tears left in situ during ACL reconstruction and compared the results with those of matched patients with intact menisci at the time of ACL reconstruction. After a mean follow-up period of 10.6 years, no differences in subjective or objective scores were observed between the 2 groups. Patients with a posterior lateral root tear showed only slight lateral joint space narrowing compared with the control group. Anderson et al. studied the outcome after repair of a posterior root tear, and they could show that these injuries have the potential to heal. However, they speculated that not all posterior lateral root tears may require repair. If the posterior lateral meniscus horn is still attached to the posterior MFL, root repair may not be necessary. These data from clinical studies are consistent with our findings.

A clinical study has shown that a lateral meniscus root tear and the loss of the MFL anchor contribute to

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### Table 2. Peak Pressure in Lateral Compartment

<table>
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<tr>
<th>Condition</th>
<th>Mean</th>
<th>SD</th>
<th>Minimum</th>
<th>Maximum</th>
<th>25th Percentile</th>
<th>50th Percentile (Median)</th>
<th>75th Percentile</th>
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</thead>
<tbody>
<tr>
<td>Intact</td>
<td>443</td>
<td>87.94569</td>
<td>280</td>
<td>570</td>
<td>380</td>
<td>440</td>
<td>512.5</td>
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<tr>
<td>Root tear</td>
<td>543</td>
<td>157.4131</td>
<td>320</td>
<td>780</td>
<td>422.5</td>
<td>495</td>
<td>705</td>
</tr>
<tr>
<td>Root tear and transection of MFL</td>
<td>1,438</td>
<td>635.6589</td>
<td>950</td>
<td>2,550</td>
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<td>1,165</td>
<td>1,987.5</td>
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<tr>
<td>Anatomic fixation</td>
<td>514</td>
<td>167.478</td>
<td>320</td>
<td>780</td>
<td>357.5</td>
<td>490</td>
<td>695</td>
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<td>Fixation through ACL tunnel</td>
<td>481</td>
<td>161.345</td>
<td>220</td>
<td>730</td>
<td>355</td>
<td>485</td>
<td>635</td>
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</table>

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**Fig 8.** Box-plot diagram of mean pressure in defined ROI in lateral compartment. (anat, anatomic; refix, refixation.)
meniscal extrusion on magnetic resonance imaging.\textsuperscript{12} In the case of a medial meniscus root tear, Brody et al.\textsuperscript{12} found an incidence of medial meniscus extrusion of 88%. In the case of a lateral meniscus root tear, they found an incidence of lateral meniscus extrusion of only 23%. Although meniscus extrusion was not measured in our study, one might assume that the intact MFL prevents meniscus extrusion in the case of a root tear. The difference between the peak pressure and the mean pressure of a defined ROI around the peak pressure spot might be a hint regarding the expected decrease in the contact zone and the concentration of load transmission to a smaller area in the case of a cut of both posterior attachments. These findings are consistent with the results of Bao et al.\textsuperscript{10} They described a reduction of the contact area from about 500 mm\textsuperscript{2} down to 350 mm\textsuperscript{2} in a finite-element analysis in the case of a combination of a lateral meniscus root tear and rupture of the MFL.

Many fixation techniques for lateral meniscus root tears have been described.\textsuperscript{7,15,19-21} The effectiveness of a transosseous suture repair technique was shown by Schillhammer et al.\textsuperscript{9} Stärke et al.\textsuperscript{22} showed that a nonanatomic position of the horn attachment strongly affects the conversion of femorotibial loads into circumferential tension. These findings are in contrast to the findings of our study. However, the posterior root attachment is located directly posterior to the posterolateral border of the ACL tibial insertion\textsuperscript{23,24} (Fig 9). This close topographic relation may explain why there was no significant difference between the 2 different fixation techniques tested in our study. Fixation of the posterior root of the lateral meniscus through the tibial ACL tunnel is technically easier than when performed through a second tunnel. The technique requires only 1 tunnel to fixate the posterior horn of the lateral meniscus and to perform the ACL reconstruction. Problems of tunnel preparation such as intersecting tunnels can be avoided. After preparation of the insertion site of the lateral meniscus posterior horn, applying gentle tension on the transtibial pullout sutures guarantees fixation to the anatomic insertion and avoids over-retention of the posterior horn into the joint space. However, further clinical studies are needed to examine whether posterior root tears of the lateral meniscus heal when repaired with this technique.

**Limitations**

A biomechanical time-zero study does not regard a possible stabilizing effect of muscles and soft tissues. The setup used does not provide any free range of motion of the tibia and investigates the effect of lateral meniscus root tears and different fixation techniques on the intra-articular pressure in full extension only. The stabilizing effect of the MFL and the effect of a root repair might be influenced by different flexion angles and movement of the tibia. In this study a load of 100 N and a loading rate of 20 N/s were used. Future studies should apply a higher load to measure the effect under full weight-bearing conditions.

**Conclusions**

In the case of a posterior root tear of the lateral meniscus, the MFL maintains meniscus function and stabilizes the pressure in the lateral compartment. A complete detachment of the posterior meniscus horn (MFL and root tear) leads to a significant increase in the intra-articular pressure and needs to be fixated. A root repair normalizes the pressure down to normal values. The pullout repair through the tibial ACL tunnel guarantees a restoration of the intra-articular pressure down to normal values in the lateral compartment. Fixation through the ACL tunnel is equivalent to a pullout repair through an additional tunnel in the lateral compartment.

### Table 3. Mean Pressure in Defined ROI in Lateral Compartment

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>SD</th>
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<th>Maximum</th>
<th>25th Percentile</th>
<th>50th Percentile (Median)</th>
<th>75th Percentile</th>
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<tr>
<td>Intact</td>
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<td>Root tear</td>
<td>306.481</td>
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<tr>
<td>Root tear and transection of MFL</td>
<td>852.713</td>
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<td>747.495</td>
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<td>122.1276</td>
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<td>180.84</td>
<td>208.765</td>
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<td>Fixation through ACL tunnel</td>
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<td>147.26</td>
<td>506</td>
<td>186.8475</td>
<td>226.74</td>
<td>320.18</td>
</tr>
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</table>

Fig 9. Arthroscopic view of lateral compartment showing close relation of root to ACL insertion. The asterisk indicates the root insertion, and the arrow indicates the ACL fibers.
center of the root insertion site. The tibial ACL tunnel is suitable to perform the repair and to lead out the suture.

References