How to evaluate bone tunnel widening after ACL reconstruction - a critical review

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Summary

Background: Comparing different imaging modalities and methods for assessment tunnel widening after ACL reconstruction and providing a detailed evidence-based literature overview.

Methods: PubMed was searched from 1970 to 2016 using the terms “ACL reconstruction” and “tunnel” and “imaging” or “CT” or “computerized tomography” or “MRI” or “magnetic resonance imaging” or “radiographs”. 647 studies were found. 575 articles were excluded due to absence of specific radiological measurement methods of tunnel widening and 40 due to repetition of a previously published radiological measurement method. 32 articles were included reporting inter- and intraobserver reliabilities of tunnel measurement methods after ACL reconstruction.

Results: A variety of different algorithms and measurement methods using radiographs, magnetic resonance imaging, computed tomography or SPECT/CT evaluating tunnel position and bone tunnel enlargement have been described. Tunnel delination restricts an exact analysis using X-ray. Measurements using CT or MR were mostly obtained perpendicular to the tunnel axis or using specialized software for tunnel volume calculation in 3D.

Based on the review the width of the femoral and tibial tunnels should be assessed perpendicular to the tunnel axis at different levels in relation to the joint. At least one measurement should be performed at the tunnel entrance, exit and midpoint of the tunnel.

Conclusion: CT should be considered the gold standard assessing tunnel widening in patients after ACL reconstruction. If specialized software is available calculating the tunnel volume, measurements should be preferably performed in 3D CT.

Level of evidence: II.

KEY WORDS: ACL reconstruction, computed tomography, magnetic resonance imaging, tunnel widening.

Background

Bone tunnel widening is a frequently encountered phenomenon following reconstruction of the anterior cruciate ligament (ACL)1-47. The causes of tunnel widening are not fully understood, but it is believed to be multifactorial, a combination of biomechanical and biological factors. Micromotion of the graft within the tunnel is believed to lead to an inflammatory response or stress shielding.

A reliable and standardized radiological assessment of postoperative knees after ACL reconstruction is important from clinical but also research perspectives. Generally, the routine radiological assessment, whether for study purposes or clinical routine, consists of weight-bearing antero-posterior, lateral and tunnel view radiographs. However, it is often difficult to reliably identify the femoral tunnel aperture on radiographs and measure the width of the tunnel16, 45. Hence, the interpretation of absolute bone tunnel size measurements using radiographs can be misleading.

In the last decade magnetic resonance imaging (MRI) and computed tomography (CT) were increasingly used for evaluation of tunnel widening, as these promised higher accuracy and lower inter- or intraobserver variabilities9, 10, 18, 45. Only few Authors have used bone scans, single-photon emission tomography (SPECT) or multi-modality imaging such as SPECT/CT to follow-up their patients after ACL reconstruction11. 13. A variety of different algorithms and measurement methods using conventional radiographs, MRI or CT, whether in 2D or 3D have been described to evaluate bone tunnel widening1-4, 6-10, 13, 15, 17-20, 22, 23, 26, 28-33, 37-47.

With this review, we endeavor to compare the different imaging modalities and methods being available.
for assessment of patients after ACL reconstruction and provide a detailed evidence-based literature overview, which is helpful for musculoskeletal radiologists and orthopedic surgeons.

Materials and methods

We performed a PubMed literature search from 1970 to July 2016 using the terms “ACL reconstruction” and “tunnel” and “imaging” or “CT” or “computerized tomography” or “MRI” or “magnetic resonance imaging” or “radiographs”. We applied no language restriction and excluded data from abstracts or unpublished studies. The database initially was queried on July 1st, 2016. Additional articles were retrieved by expert consultation and personal files. Literature search including the aforementioned search criteria identified 647 studies for potential inclusion; for all of these articles, abstracts and fulltext were then reviewed and screened for inclusion (Fig. 1). 575 studies were excluded from this review, as these did not report specific radiological measurement methods. Excluded were also all 40 articles in which an identical measurement method to assess tunnel widening was used as reported in a previous study. Only the first study reporting a distinct measurement method was included in this review.

All landmark studies reporting different imaging modalities and methods of bone tunnel measurement were selected for this systematic review. A total of 32 studies were included in this review. This implied in particular studies reporting inter- and intraobserver reliabilities of the described evaluation methods and measurements. Analysis was done by a professional statistician, who is part of the research group. The study was done in accordance with the published guidelines of Padulo et al.48.

Results

The femoral and tibial bone tunnel widths after ACL reconstruction were assessed either using radiographs, CT, MRI or SPECT/CT. The results of the selected studies are herein summarized and highlighted in Tables I-III.

Radiographs

Peyrache et al. measured the distance between the sclerotic margins of the tibial tunnel at the distal tunnel exit on the medial tibial cortex, in the middle of the tunnel, and proximally at the level of the joint line (Fig. 2 a)30. The position of the center of the tibial tunnel line with regard to Blumensaat's line was also measured30.

L’Insalata et al. studied tunnel widening 9 months postoperatively on anteroposterior and lateral views. They used a digital caliper to measure the widest dimension. These were compared with the diameters of the fixation interference screws. The intraclass correlation coefficient was 0.92 with a confidence interval of 0.9523.

Murty et al. measured the size of the bone tunnel on radiographs as the distance between the two sclerotic margins of the bone tunnel at 5 mm from the tibial entrance and at 5 mm from the tibial exit point perpendicular to the longitudinal axis of the tunnel. The widest dimension of both measurements was used. The percentage of enlargement was calculated in relation to the original drill size. The inter-observer correlation coefficient was 0.90 and the intra-observer correlation coefficient was 0.91, indicating excellent
Table I. List of included studies presenting different methods for assessment of tunnel widening on radiographs.

<table>
<thead>
<tr>
<th>Study</th>
<th>Tunnels measured</th>
<th>Measured points</th>
<th>Measured value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peyrache et al. (1996)</td>
<td>Tibial</td>
<td>Proximal, middle, distal</td>
<td>Diameter</td>
</tr>
<tr>
<td>L'Insalata et al. (1997)</td>
<td>Tibial + femoral</td>
<td>Widest</td>
<td>Diameter</td>
</tr>
<tr>
<td>Nebelung et al. (1998)</td>
<td>Tibial + femoral</td>
<td>Femoral entrance, tibial entrance, tibial exit</td>
<td>Diameter</td>
</tr>
<tr>
<td>Murty et al. (2001)</td>
<td>Tibial</td>
<td>Widest of 5 mm from tibial entrance, 5 mm from tibial exit</td>
<td>Diameter</td>
</tr>
<tr>
<td>Baumfeld et al. (2008)</td>
<td>Tibial + femoral</td>
<td>Widest point + 1 cm from the apertures of the tibial and femoral tunnels at the joint</td>
<td>Diameter</td>
</tr>
<tr>
<td>Clatworthy et al. (1999)</td>
<td>Tibial + femoral</td>
<td>Tibial: AP + lateral – 1 cm distal of ACL attachment Femoral: AP – 1 cm proximal to physeal line, lateral – 1 cm proximal to Blumensatt's line.</td>
<td>Area</td>
</tr>
<tr>
<td>Fauno and Kaalund (2005)</td>
<td>Tibial + femoral</td>
<td>At 1 cm below the tibial plateau, 1 cm above the femoral entrance</td>
<td>Diameter</td>
</tr>
<tr>
<td>Kawaguchi et al. (2011)</td>
<td>Femoral</td>
<td>Intra-articular outlet</td>
<td>Diameter</td>
</tr>
</tbody>
</table>

Table II. List of included studies presenting different methods for assessment of tunnel widening on CT.

<table>
<thead>
<tr>
<th>Study</th>
<th>Tunnels measured</th>
<th>Views</th>
<th>Measured points</th>
<th>Measured value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Webster et al. (2004)</td>
<td>Tibial + femoral</td>
<td>Coronal, sagittal</td>
<td>Widest</td>
<td>Diameter</td>
</tr>
<tr>
<td>Siebold et al. (2008)</td>
<td>Tibial + femoral</td>
<td>Axial, oblique coronal</td>
<td>At 1 cm proximally and distally from the joint</td>
<td>Diameter</td>
</tr>
<tr>
<td>Fink et al. (2001)</td>
<td>Tibial</td>
<td>Coronal, sagittal</td>
<td>At 5 different levels with equal distance between each other</td>
<td>Diameter</td>
</tr>
<tr>
<td>Vadaia et al. (2007)</td>
<td>Tibial</td>
<td>Axial, coronal, sagittal</td>
<td>Tunnel is divided into six cross sections (5 mm wide each)</td>
<td>Volume</td>
</tr>
<tr>
<td>Foldager et al. (2010)</td>
<td>Tibial</td>
<td>Axial, coronal, sagittal</td>
<td>Trace the circumference of the tunnel with a minimum of 15 reference points and a computer automatically calculated the CSA</td>
<td>Area</td>
</tr>
<tr>
<td>Robinson et al. (2006)</td>
<td>Tibial</td>
<td>Along and perpendicular to the tunnel axis</td>
<td>Best fit cylinder is generated by a program and its diameter is recorded, area and volume is calculated by the program</td>
<td>Diameter, area, volume</td>
</tr>
<tr>
<td>Robbrecht et al. (2014)</td>
<td>Tibial + femoral</td>
<td>3D</td>
<td>At 15 mm and 20 mm from the tip of the posterior wall of the tunnel</td>
<td>Area</td>
</tr>
<tr>
<td>Yang et al. (2014)</td>
<td>Tibial</td>
<td>Axial, sagittal</td>
<td>At aperture, midway, and suspension point</td>
<td>Diameter</td>
</tr>
<tr>
<td>Silva et al. (2013)</td>
<td>Tibial</td>
<td>Axial, Sagittal</td>
<td>At aperture site, 5 and 10 mm from the aperture site</td>
<td>Area</td>
</tr>
<tr>
<td>Sabat et al. (2011)</td>
<td>Tibial + femoral</td>
<td>Oblique coronal, oblique sagittal</td>
<td>Horizontal diameter: width of the femoral tunnel aperture along the Blumensaat line. Vertical diameter: height of the femoral tunnel aperture perpendicular to Blumensaat Line.</td>
<td>Diameter</td>
</tr>
<tr>
<td>Tachibana et al. (2014)</td>
<td>Femoral</td>
<td>3D</td>
<td>The region of bone tunnel is extracted, the voxel of the region is counted and is translated into the volume</td>
<td>Volume</td>
</tr>
<tr>
<td>Taketomi et al. (2014)</td>
<td>Femoral</td>
<td>3D</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Araki et al. (2014)</td>
<td>Tibial + femoral</td>
<td>3D</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Matsumoto et al. (2014)</td>
<td>Tibial + femoral</td>
<td>3D</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Huang et al. (2012)</td>
<td>Tibial + femoral</td>
<td>Sagittal CT, lateral X-ray</td>
<td>At 2 mm below the articular surface</td>
<td>Diameter</td>
</tr>
</tbody>
</table>
Table III. List of included studies presenting different methods for assessment of tunnel widening on MRI.

<table>
<thead>
<tr>
<th>Study</th>
<th>Tunnels measured</th>
<th>Views</th>
<th>Measured points</th>
<th>Measured value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kopf et al. (2010)</td>
<td>Tibial + femoral</td>
<td>axial</td>
<td>At the bone tunnel aperture and 1 cm deep to the aperture</td>
<td>Diameter, area</td>
</tr>
<tr>
<td>Silva et al. (2010)</td>
<td>Femoral</td>
<td>coronal oblique</td>
<td>At the entrance of the femoral tunnel and at the point where they were largest</td>
<td>Diameter</td>
</tr>
<tr>
<td>Järvelä et al. (2008)</td>
<td>Tibial + femoral</td>
<td>oblique coronal, sagittal</td>
<td>At 2 cm from the articular surface</td>
<td>Diameter</td>
</tr>
<tr>
<td>Buelow et al. (2002)</td>
<td>Tibial + femoral</td>
<td>coronal, sagittal</td>
<td>At 1 cm proximal to the ACL origin and 1 cm distal to the ACL insertion</td>
<td>Area</td>
</tr>
<tr>
<td>Fules et al. (2003)</td>
<td>Tibial</td>
<td>axial</td>
<td>At 1 cm above the distal tibial tunnel exit and at the midpoint of the tunnel</td>
<td>Area</td>
</tr>
<tr>
<td>Frosch et al. (2009)</td>
<td>Tibial + femoral</td>
<td>sagittal</td>
<td>Tunnel is divided into three sections, the maximal diameter of each third is measured</td>
<td>Area</td>
</tr>
<tr>
<td>Kim et al. (2013)</td>
<td>Tibial</td>
<td>axial</td>
<td>At 1 cm below the articular surface, 1 cm above the distal tibial tunnel exit and at the midpoint of the tunnel</td>
<td>Area</td>
</tr>
</tbody>
</table>

reliability. Baumfeld et al. measured the femoral and tibial tunnel widths at the widest point and at 1 cm from the aperture of both tunnels. Measurements were made perpendicular to the long axis of the tunnels. The absolute values in mm and the percentages of enlargement were calculated in relation to the original drill size. The inter-rater reliability was excellent.

Clatworthy et al. evaluated tunnel widening in a prospective matched series of patients after hamstring and patella tendon autograft ACL reconstruction. Tunnel widening was determined using standardized anteroposterior and lateral radiographs adjusted for magnification. The femoral tunnel diameter was determined on the anterior-posterior radiograph 1 cm proximal to the epiphyseal line and on the lateral radiograph 1 cm proximal to Blumensaat’s line. The tibial tunnel diameter was determined on both radiographs 1 cm distal to the ACL attachment. Area was chosen over width as the tunnels are three-dimensional structures.

Fauno and Kaalund measured the tibial and femoral tunnel width 1 cm below the tibial plateau and 1 cm above the femoral entrance on standardized anteroposterior and lateral radiographs (Fig. 2 b). The margins of the tunnels were measured by a single observer. No reliability testing was reported.

Nebelung et al. defined six measurement points, three each on anterior-posterior and lateral radiographs (femoral entrance point, tibial entrance point, tibial exit point) (Fig. 2 c). The absolute values were compared to the size of the drill bit at surgery. Tunnel enlargement was defined as more than 2.5 mm of the drill bit size, clear enlargement as 2.5-4.5 mm and massive enlargement as more than 4.5 mm, whereas borderline enlargement was defined as 0.5-2 mm. Kawaguchi et al. compared femoral tunnel widening between single-bundle and anatomic double-bundle ACL reconstructions with hamstring tendon grafts. The tunnel measurement was taken at the intra-articular outlet of the femoral tunnels in each plane, perpendicular to the direction of the long axis of the tunnels.

Surer et al. divided the longitudinal axis of the bone tunnel into three equal portions. In each portion, the width of the tunnel was measured at the widest part. This was done for the femoral and tibial tunnel on the AP radiograph and for the tibial tunnel only on the lateral radiograph, since the femoral tunnel is not easily identifiable on this view. The radiographs were taken immediately post-operatively, as well as at 1-year follow-up to calculate the amount of tunnel widening that had occurred.

**CT**

Fink et al. digitally measured the width of the tibial tunnel on 1 mm thin sagittal- and coronal-reformatted CT images at five different levels (Fig. 3 a). The levels ranged from the joint line to the bone block and divided the tibial tunnel in five equal horizontal parts. Sabat et al. assessed tibial and femoral tunnel diameters by three points on 1 mm thick both oblique sagittal and oblique coronal images. First point was the aperture of the tunnels, second point the proximal or distal suspension of the tunnel and third point the maximal diameter of the tunnel (Fig. 3 b). Webster et al. used 1 mm axial CT slices, which were orientated in the axes of the femoral and tibial tunnels, for determination of the femoral and tibial tunnel widths 12 months postoperatively. The measurement was performed on the image showing the widest tunnel in sagittal and coronal planes (Fig. 3 c). The size of the tunnel was given as absolute values and in relation to the diameter of the used drill bit at surgery. Inter-rater variability was 0.81.

Siebold et al. measured the diameter of the tibial and
femoral bone tunnels perpendicular to the long axis of the tunnels on oblique coronal and axial planes. On the femoral and tibial side the measurements were performed approximately 1 cm proximally or distally from the joint. Absolute diameters as well as relative values were calculated as a percentage of the diameter of the drill bit used at surgery. Iorio et al. and Vadala et al. determined the transosseous diameters of the femoral and tibial tunnels at four different levels on sagittal, coronal and axial CT images (femoral tunnel at the notch and at the midpoint on axial slices and at the midpoint on coronal and sagittal reformations; tibial tunnel on axial and sagittal reformations at the level of the plateau and at the midpoint). The slice thickness used was 1 mm and 0.75 mm, respectively. Foldager et al. assessed tunnel widening on CT following ACL reconstruction using poly-lactide carbonate interference screws. The 0.9 mm slice thickness CT images were reconstructed in the direction of the
The tunnel was divided into six cross sections, each 5 mm wide. The diameter was measured in the horizontal and the vertical plane and the cross-sectional areas were calculated using the mean diameter between the horizontal and vertical measurement under the assumption that the tunnel was circular shaped. Furthermore the tunnel volume in mm$^3$ was characterized.

Robinson et al. assessed tibial tunnel cross-sectional area on CT. 1 mm thin CT images were reconstructed along and perpendicular to the tibial tunnel axis. The circumference of the tunnel was traced with a minimum of 15 reference points and the cross-sectional area was automatically calculated.

Tachibana et al. determined the femoral tunnel cross-section area by measuring at three planes, perpendicular to the long axis, created at the aperture site, 5 and 10 mm from the aperture site on a 3D model. Slice thickness used was 0.625 mm.

Robbrecht et al. and Yang et al. used axial CT images (0.625 mm thick) to segment and reconstruct the bone into a 3D model by a computer program; the femoral and tibial tunnels were separately analyzed by the program. Best fitted cylinder was generated and its diameter was recorded, area and volume were calculated.
Taketomi et al. measured the width of the femoral tunnel aperture along the Blumensaat line and the height of the femoral tunnel aperture perpendicular to the Blumensaat line on 3D CT.[42] Silva et al. investigated tibial tunnel enlargement by measuring the tunnel’s cross-sectional area on 2 mm thick axial and sagittal images at 15 mm and 20 mm from the tip of the posterior wall of the tunnel.[39] Araki et al. and Matsumoto et al. used 3D CT images with 1 mm slice thickness. Each CT image consisted of 512 voxels. The region of bone tunnel was manually identified in each slice, the voxel of the region was counted, and finally, the total amount of the voxel could be translated into the volume[1, 26].

**MRI**

Kopf et al. evaluated the bone tunnel size in patients with open growth plates after transphyseal ACL reconstruction[22]. The cross-sectional area of the tunnels was assessed on axial MRI perpendicular to the tunnel axis[22]. The widest tunnel diameter was measured at joint line and 1 cm proximally or distally and another tunnel diameter perpendicular to it. The percentages of the absolute values to the original drill bit size were calculated[22]. Silva et al. investigated femoral tunnel widening on contrast-enhanced MRI. Three different sequences of MR images were obtained for each tunnel (T1-weighted, proton-density-weighted fat-saturated and T1-weighted fat-saturated images after intravenous contrast administration)[38]. The diameters of each tunnel were measured perpendicular to the long axis of the tunnel at the tunnel aperture and at their widest point[38]. Buelow et al. measured the tunnel diameter on radiographs (antero-posterior and lateral weight-bearing in extension)[3]. The femoral and tibial tunnel diameters were measured 1 cm above or below the intraarticular surface[3]. The absolute and relative femoral and tibial bone tunnel areas were calculated[3]. The tunnel measurements were repeated on sagittal and coronal MR images and then compared to the measurements on radiographs (Fig. 4 a)[3]. Järvelä et al. assessed the widest anterior-posterior and medial-lateral tunnel diameter (2 cm apart from tunnel entrance) using oblique coronal and sagittal MR images after double-bundle ACL reconstruction (Fig. 4 b)[18]. Absolute tunnel diameters as well as percentages in relation to the size of the drill bit used at surgery were given[18]. Fules et al. assessed the tibial bone tunnel widening on MRI following four-strand hamstring tendon ACL reconstruction[10]. T1- and T2-weighted axial sequences were orientated perpendicular to the long axis of the tibial tunnel[10]. Measurements of the three-dimensional cross-sectional area were performed at three different levels (1 cm below the articular surface, at the midpoint of the tunnel and 1 cm above the distal tibial tunnel exit) using a computer generated best-fit model[10]. Absolute and relative values of the tunnel cross-sectional area were reported[10]. Frosch et al. measured the width of the bone tunnels perpendicular to the tunnel axis in the sagittal plane[9]. The widest diameter was measured in three equal parts and the cross-sectional area was calculated (Fig. 4 c)[9]. The absolute and relative values in relation to the drill bit were used[9]. Kim et al. assessed tibial tunnel cross-sectional area by T1- and T2-weighted axial images which were obtained perpendicular to the long axis of the tibial tunnel 1 cm below the articular surface, 1 cm above the distal tibial tunnel exit, and at the midpoint of the tunnel[20]. Weber et al. conducted an MRI of the operative knee immediately after ACL reconstruction on postoperative day zero, as well as 6, 12, 24, 52, and 104 weeks postoperatively[44]. Measures of tunnel cross-sectional area were calculated perpendicular to the long axis of the tunnel at 3 distinct and standardized locations along both the tibial and femoral tunnels in both the sagittal and coronal planes. The tibial and femoral tunnel aperture measurements were calculated 0.5 cm from the joint-tunnel interface. The tibial and femoral tunnel midsection measurements were calculated at the midline of the longitudinal axis of the tunnel. The tibial and femoral exit measurements were calculated 0.5 cm from the termination of the tunnel.[44].

**SPECT/CT**

Hirschmann et al. highlighted the clinical potential of SPECT/CT imaging in evaluating tunnel widening after ACL reconstruction[13]. It promises the potential assessment of the biology of the joint and particularly the integration or healing of the bone-graft-fixation complex, which might be beneficial in patients with biocompatible interference screws[13]. The measurement of tunnel width was performed descriptively, but correlated with additional information from SPECT about joint homeostasis[13].

** Discussion**

A variety of imaging methods such as radiographs, CT, MRI or SPECT/CT have been used to assess tunnel widening in patients after ACL reconstruction[1-4, 6-10, 13, 15, 17-20, 22, 23, 26, 28-33, 37-47]. To date, it seems that the selection for an appropriate imaging modality depends predominantly on the availability of imaging modality and the preference of the investigator than on clinical evidence. However, there are clearly pros and cons related to each imaging modality. Radiographs offer the benefit of widespread availability. The measurement of tunnel width can be easily performed, either with calipers or digitally[2, 4, 6, 19, 23, 28-30, 40, 45]. Most frequently, the widest diameters of the tunnels at one or several tunnel heights were measured[2, 4, 6, 19, 23, 28-30, 40, 45]. This simplified measurement does not adequately represent the real bone tunnel width as they show irregular and more or less sclerotic tunnel walls. Although using antero-posterior and lateral radiographs this approach oversimplifies the shape and size of the bone tunnels.
Previous studies demonstrated that measuring bone tunnels on radiographs may result in underestimation of the real tunnel diameter. A major drawback of the assessment of tunnel widening on radiographs is its poor inter- and intra-observer reliability. The magnitude of measurement error between two follow-ups in one patient depends on the variability of the patient's knee in the X-ray beam, the contrast of radiographs and the individual measurement error. In addition, a considerable number of tunnels are not easily identified on radiographs, which is particularly true for patients with long-term follow-up after ACL reconstruction.

To overcome these limitations of radiographs as a 2D imaging modality in the evaluation of tunnel widening, 3D imaging modalities have been increasingly used. Most of the authors used CT images with two reformatted planes for evaluating bone tunnel widening after ACL reconstruction. CT images promise the more accurate assessment of the size and shape of the tunnel walls. The tunnel walls were either evaluated in reformatted planes or on 3D volume rendering images. Fink et al. showed that computed tomography is superior to plain radiographs for evaluating bone tunnel enlargement on the tibial side, especially in the early postoperative phase, when the tunnel margins are sometimes hard to identify on radiographs. In addition, measurement of the tunnel width on CT images is less dependent on the patient position in the scanner and therefore significantly reduces the degree of measurement error. Most authors assessed the cross-sectional area of the tunnels on axial CT scans perpendicular to the tunnel axis. The widest tunnel diameter was noted at one to eight different levels in relation to the joint. The percentages of the absolute values to the original drill bit size were calculated.

In contrast to CT, MRI promises not only structural information on the tunnels, but also allows evaluation of the ACL graft itself. Major drawback is the limited assessment of osseous structures in MRI. Most authors assessed the cross-sectional area of the tunnels on axial MR images perpendicular to the tunnel axis. The widest tunnel diameter was noted at different levels in relation to the joint. The percentages of the absolute values to the original drill bit size were calculated. Susceptibility artifacts, caused by metallic implants such as buttons, screws or pins, which are commonly used in ACL surgery, can limit...
the evaluation of both femoral and tibial tunnels. Jansson et al. concluded that in clinical routine, radiographic measurements are more suitable and reliable in evaluating tunnel width than MRI.\(^{17}\)

We hereby acknowledge substantial limitations of our review largely reflecting limitations in the existing body of literature. There are only a few studies reporting the inter- and intraobserver reliability of their measurement method, which would be crucial for defining their technical feasibility and hence their clinical value.

In summary, CT imaging should be considered the gold standard assessing tunnel widening in patients after ACL reconstruction. Width of the femoral and tibial tunnels should be assessed perpendicular to the tunnel axis at different levels in relation to the joint. At least one measurement should be performed at the tunnel entrance, exit and midpoint of the tunnel. If specialized software is available calculating the tunnel volume, measurements should be preferably performed in 3D CT.

Author contributions

Koch JEJ, de Beus A, Hirschmann A and Hirschmann MT contributed equally to the work; Hirschmann MT conceptualized and designed the review together with de Beus A; Koch JEJ and Hirschmann MT carried out the analysis; Koch JEJ, de Beus A, Hirschmann A and Hirschmann MT drafted the initial manuscript; all Authors reviewed and approved the final manuscript as submitted.

Conflict of interest

The Authors have no conflict of interest to be reported with regards to this paper.

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