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 delineation 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 mid-point 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 tunnel^{16, 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 intra-observer variabilities^{9, 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 reconstruction^{11, 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 widening^{1-4, 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

Figure 1. Flow chart of inclusion and exclusion criteria.

Table I. List of included studies presenting different methods for assessment of tunnel widening on radiographs.

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

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

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

Table III. List of included studies presenting different methods for assessment of tunnel widening on MRI.

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

reliability²⁸.

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 excellent².

Clatworthy et al. evaluated tunnel widening in a prospective matched series of patients after hamstring and patella tendon autograft ACL reconstruction⁴. 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 line⁴. 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 structures⁴.

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)⁶. The margins of the tunnels were measured by a single observer. No reliability testing was reported⁶.

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 mm²⁹.

Kawaguchi et al. compared femoral tunnel widening between single-bundle and anatomic double-bundle

ACL reconstructions with hamstring tendon grafts¹⁹. 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 tunnels¹⁹.

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 part⁴⁰. 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 occurred⁴⁰.

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 parts⁷. 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)³³.

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 postoperatively⁴⁶. 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 0.81⁴⁶.

Siebold et al. measured the diameter of the tibial and

Figure 2 a-c. Illustration of different measurement methods on anterior-posterior and lateral knee radiographs. a) Peyrache et al. measured both tunnels at three different heights in two projections³⁰. b) Fauno and Kaalund measured the femoral tunnel width 1 cm above the tunnel entrance and the tibial tunnel width 1 cm below the entrance⁶. c) Nebelung et al. measured both tunnel widths at the entrance and additionally the tibial tunnel widths at the exit²⁹.

femoral bone tunnels perpendicular to the long axis of the tunnels on oblique coronal and axial planes³⁷. 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 surgery³⁷. 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^{15, 43}. Foldager et al. assessed tunnel widening on CT following ACL reconstruction using poly-lactide carbonate interference screws⁸. The 0.9 mm slice thickness CT images were reconstructed in the direction of the

Figure 3 a-c. Illustration of different measurement methods of the tibial tunnel on coronal, sagittal and axial CT images. a) Fink et al. measured the tibial tunnel widths at five different levels with equal distances between each other⁷. b) Sabat et al. measured the tibial tunnel width at three different levels, the entrance, the exit and the widest part³³. c) Webster et al. measured the tibial tunnel width at the widest distance⁴⁵.

tibial tunnel. The tunnel was divided into six cross sections, each 5 mm wide⁸. 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 mm³ was characterized⁸.

Robinson et al. assessed tibial tunnel cross-sectional area on CT³². 1 mm thin CT images were reconstructed along and perpendicular to the tibial tunnel axis³². The circumference of the tunnel was traced with a minimum of 15 reference points and the cross-sectional

area was automatically calculated³².

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 model⁴¹. Slice thickness used was 0.625 mm⁴¹.

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^{31, 47}. Best fitted cylinder was generated and its diameter was recorded, area and volume were calculated^{31, 47}.

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 CT⁴².

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 tunnel³⁹.

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 reconstruction²². The cross-sectional area of the tunnels was assessed on axial MRI perpendicular to the tunnel axis²². 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 calculated²².

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 point³⁸.

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 intra-articular surface³. The absolute and relative femoral and tibial bone tunnel areas were calculated³. 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 given¹⁸.

Fules et al. assessed the tibial bone tunnel widening on MRI following four-strand hamstring tendon ACL reconstruction¹⁰. T1- and T2-weighted axial sequences were orientated perpendicular to the long axis of the tibial tunnel¹⁰. 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 model¹⁰. Absolute and relative values of the tunnel cross-sectional area were reported¹⁰.

Frosch et al. measured the width of the bone tunnels

perpendicular to the tunnel axis in the sagittal plane⁹. 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 used⁹.

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 tunnel²⁰.

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 postoperatively⁴⁴. 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 tunnel⁴⁴.

SPECT/CT

Hirschmann et al. highlighted the clinical potential of SPECT/CT imaging in evaluating tunnel widening after ACL reconstruction¹³. 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 screws¹³. The measurement of tunnel width was performed descriptively, but correlated with additional information from SPECT about joint homeostasis¹³.

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.

Figure 4 a-c. Illustration of different measurement methods for the tibial tunnel on MRI (oblique coronal, sagittal and axial images). a) Buelow et al. measured the tibial tunnel width 1 cm distal to the ACL insertion³. b) Järvelä et al. measured the tibial tunnel width 2 cm apart from the entrance¹⁸. c) Frosch et al. divided the tibial tunnel into three parts and measured the largest tunnel widths at each of the three parts⁹.

Previous studies demonstrated that measuring bone tunnels on radiographs may result in underestimation of the real tunnel diameter⁴⁵.

Major drawback of the assessment of tunnel widening on radiographs is its poor inter- and intra-observer reliability^{7, 45}. 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^{7, 45}. 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^{7, 45}.

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^{1, 7, 8, 15, 26, 31-33, 37, 39, 41-43, 46, 47}. 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^{7, 16}. 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 error⁷. Most Authors assessed the cross-sectional area of the tunnels on axial CT scans perpendicular to the tunnel axis^{1, 7, 8, 15, 26, 31-33, 37, 39, 41-43, 46, 47}. The widest tunnel diameter was noted at one to eight different levels in relation to the joint^{1, 7, 8, 15, 26, 31-33, 37, 39, 41-43, 46, 47}. The percentages of the absolute values to the original drill bit size were calculated^{1, 7, 8, 15, 26, 31-33, 37, 39, 41-43, 46, 47}.

In contrast to CT, MRI promises not only structural information on the tunnels, but also allows evaluation of the ACL graft itself^{3, 9, 10, 17, 18, 20, 22, 38, 44}. 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^{3, 9, 10, 17, 18, 20, 22, 38, 44}. The percentages of the absolute values to the original drill bit size were calculated^{3, 9, 10, 17, 18, 20, 22, 38, 44}. 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 MRI¹⁷.

We hereby acknowledge substantial limitations of our review largely reflecting limitations in the existing body of literature. There are only 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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