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# Radiographic positions of femoral ACL, AM and PL centres: accuracy of guidelines based on the lateral quadrant method

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**Abstract**
*Purpose* Femoral tunnel positioning is an important factor in anatomical ACL reconstructions. To improve accuracy, lateral radiographic support can be used to determine the correct tunnel location, applying the quadrant method. Piefer et al. (Arthroscopy 28:872–881, 2012) combined various outcomes of eight studies applying this method to one guideline. The studies included in that guideline used various insertion margins, imaging techniques and measurement methods to determine the position of the ACL centres. The question we addressed is whether condensing data from various methods into one guideline, results in a more accurate guideline than the results of one study.
*Methods* The accuracy of the Piefer's guideline was determined and compared to a guideline developed by Luites et al. (2000). For both guidelines, we quantified the mean absolute differences in positions of the actual anatomical centres of the ACL, AM and PL measured on the lateral radiographs of twelve femora with the quadrant method and the positions according to the guidelines.
*Results* The accuracy of Piefer's guidelines was 2.4 mm (ACL), 2.7 mm (AM) and 4.6 mm (PL), resulting in positions significantly different from the actual anatomical centres. Applying Luites' guidelines for ACL and PL resulted in positions not significantly different from the actual centres. The accuracies were 1.6 mm (ACL) and 2.2 mm (PL and AM), which were significantly different from Piefer for the PL centres, and therefore more accurate.
*Conclusions* Condensing the outcomes of multiple studies using various insertion margins, imaging techniques and measurement methods, results in inaccurate guidelines for femoral ACL tunnel positioning at the lateral view.
*Clinical relevance* An accurate femoral tunnel positioning for anatomical ACL reconstruction is a key issue. The results of this study demonstrate that averaging of various radiographic guidelines for anatomical femoral ACL tunnel placement in daily practice, can result in inaccurate tunnel positions.
*Level of evidence* Diagnostic study, Level 1.

**Keywords** Anterior cruciate ligament reconstruction · Anteromedial and posterolateral bundle femoral centres · Lateral radiographic position · Quadrant method · Accuracy

## Introduction

The success of ACL reconstructions depends on various aspects. Tunnel placement is one of the most important factors influencing the clinical outcome [11, 40]. Knowledge of the anatomical position of ACL attachments can improve correct positioning and placement of the tunnel and graft. Therefore, many studies have described the anatomical position of the ACL and its functional bundles, the anteromedial (AM) and posterolateral (PL), with various methods in the past decades. Radiographic imaging has been often used to determine the centre positions, resulting in several guidelines. These guidelines can intra-operatively be used for tunnel positioning (determining the preferred position) and placement (drilling the tunnel

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**Table 1** Relative positions of the centres (%) of the ACL, AM and PL according to the guidelines of Luites et al. (2000) and Piefer et al. [43] and the positions of the actual anatomical centres in the current study in deep–shallow direction at Blumensaat's line (BS) and high–low direction at condyle depth (CD)

| | ACL | | | AM | | | PL | | |
|---|---|---|---|---|---|---|---|---|---|
| | Piefer et al. [38] | Luites et al. (2000) | Current study | Piefer et al. [38] | Luites et al. (2000) | Current study | Piefer et al. [38] | Luites et al. (2000) | Current study |
| Deep–shallow % at BS | 28.5 | 23.5 (3.7) | 24.9 (2.7) | 21.5 | 21.0 (3.6) | 23.2 (2.7) | 32.0 | 26.6 (5.3) | 25.2 (2.7) |
| High–low % at CD | 35.2 | 32.3 (7.1) | 31.9 (4.8) | 23.1 | 19.2 (10.3) | 15.1 (6.0) | 48.8 | 42.2 (9.4) | 38.1 (6.6) |

at the preferred position) and are also frequently used for post-operative tunnel placement evaluation [35]. Two main approaches can be distinguished: either lateral or coronal radiographic imaging. Studies using the frontal approach at the coronal radiographs, describe the attachment site using the so-called clock-method [37, 48], which is also often mentioned in studies using other methods [2, 10, 29, 31, 33]. However, this method has been criticized; the anatomical notch is not circular, and a two-dimensional clock is inaccurate to align in a three-dimensional structure [2, 10, 14]. Lack of a unified definition applying the clock, results in subjective placement with a diverse range of alignment and centring the clock [4, 16], providing the method a poor intra-observer and inter-observer agreement [46]. With the lateral radiographic imaging technique, various methods to describe the positions on the images have been developed [1, 2, 15, 17, 25], of which the most well-known method is the quadrant method of Bernard et al. [5]. In 2000, Luites et al. presented guidelines for AM and PL centre positions according to this lateral method at the 9th ESSKA congress (poster presentation ESSKA 2000 in London; Table 1). Thereafter, in the last decade, the quadrant method has been applied by many other research groups, resulting in various outcomes [6, 13, 15, 18, 24, 27, 28, 35, 39, 43–45, 47 49]. These variations in outcome can have multiple causes. Firstly, the attachments and attachment centres or tunnel centres have been defined in various ways. Secondly, there is a variety used in imaging techniques, such as CT scans, radiographs or digital photographs, and measurement techniques, such as callipers or digital software. Thirdly, there are differences caused by subjective macroscopic dissection of the AM and PL bundles [18]. To condense the many methods from lateral images to one set of guidelines, Piefer et al. [38] combined in 2012 the results of eight different studies [6, 13, 15, 18, 39, 43, 45, 49]. In this way, he has proposed quadrant guidelines for AM, PL and ACL centre positions (Table 1). However, since these data are composed from different studies, using different dissection concepts, it is not possible for surgeons to connect the values of these averaged guidelines to a placement concept they intend to follow. This is in contrast to guidelines from a single study. Besides that, it is questionable whether the combination and subsequent averaging of these inconsistent data sets obtained with different dissection, imaging and measurement techniques result in valid guidelines.

To answer this question, this study was performed, to assess in more detail the effects of the application of the combined guideline as defined by Piefer et al. [38] in terms of the position errors in the individual knee and compared it with a plain set of guidelines. The guidelines were applied according to Luites et al. (2000) and Piefer et al. [38] on new dissected cadaver femora, to determine the accuracy of both guidelines relative to the actual anatomical centres, i.e. the gold standard. Our hypothesis was that the mean radiographic guidelines of Luites et al. (2000) are more accurate than the composed guidelines according to Piefer et al. [38], since condensing different inconsistent methods will result in less accurate guidelines.

## Materials and methods

Twelve embalmed cadaveric knee specimens from the anatomical laboratory, without gross deformation, were dissected removing skin and muscles. Dorsal knee capsula, collateral ligaments and meniscal structures were kept intact. The synovial structure at the anterior cruciate ligament was removed to improve visibility of the fibres. The ligament showed a narrow midsubstance, with the fibres fanning out towards the femoral and tibial insertion sites, with the femoral fibres attaching to the distal convex lateral surface of the intercondylar notch. During repeated knee movement over the complete range of motion combined with an anterior translation of the tibia in the lower flexion angles, the ACL fibres remaining tightened over the complete range of motion were separated from the fibres tensed in extension and loosening with increasing flexion, with a blunt scalpel. In some specimens, a cleft was discernible between the two bundles. When separation was completed at the mid-ligamental part, the knee joint was dissected till the bone, except for the ACL. Then, separation was continued towards the tibial bone and femoral bone, after which the ligament was split. The complete insertion sites, with the fanning fibre bundles, of the ACL footprints were marked next to the outlines of the fibre attachments with a marker with permanent ink, as was the line separating the ACL into an AM and PL bundle. Then, the fibres were removed from its insertion sites. To make the insertions visible on radiographs, thin radiopaque lead wires were glued at its outlines.

The femora were embedded in a block of poly methyl methacrylate (PMMA) with the use of a mould, in a neutral position in all three planes: frontal, sagittal and transversal. True lateral radiographs were taken, positioning the femora with the medial epicondyle on top of the film including a ruler close to it. This method resulted in very small magnification effects due to roentgen beams spreading being nearly similar in all radiographs (101–102 %) and was therefore neglected. The radiographs were digitized with a Hewlett Packard Scanjet 6100 C/T (150 pixels per inch). Digital measurements of the femoral dimensions and insertion geometry were done with an accuracy of 0.1 mm in Rhinoceros (version 1.0, NURBS Modelling for Windows). To define the dimensions of the femoral condyle, the most proximal (1) and distal (2) points of the condyle at the intercondylar roof and the most dorsal (3) point of the condyle were marked. The length of Blumensaat's line (BS) was defined between point 1 (deep) and 2 (shallow); the length of the condyle depth (CD) was defined between point 3 (low) and the intersection point from its perpendicular line at BS (high). The gold standard to which the accuracy of the guidelines was calculated, is the actual position of the ACL centres from the used cadaveric knees. To define its positions, the outlines of the ACL footprint and the AM and PL bundles were marked with equally divided points. The points were converted to surfaces, and with the 'mass properties' command, the area centroid was defined. Lines from the centre towards BS and CD were drawn. Finally, the lengths of all lines (mm) were determined to define the positions of the ACL, AM and PL centre, absolutely and relative to BS and CD (Fig. 1). The ACL, AM and PL centres obtained will be referred to as 'actual ACL, AM, PL', respectively.

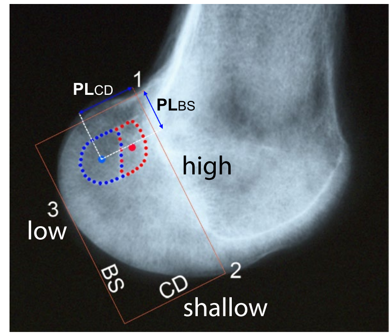


**Fig. 1** Lateral radiograph with the *lines* defining the dimensions: Blumensaat's line (*BS*) between point 1 (*deep*) and 2 (*shallow*) and condyle depth (*CD*) between point 3 (*low*) and *BS* (*high*). The actual centres of the ACL and the AM and PL bundles were defined and its positions relative to *BS* and *CD* determined

### Data analysis

To calculate the accuracy of the guidelines from Luites et al. (2000) and Piefer et al. [38], both sets (Table 1) were applied to the 12 knees and compared to the 'actual centres'. This was done in both directions, deep–shallow (BS) and high–low (CD), for the ACL, AM and PL centres. For every knee, the recommended percentages of both guidelines (Table 1) were applied and, using the individual lengths of BS and CD, recalculated into positions expressed in mm. Then, the individual differences in the centre positions according to both guidelines and the gold standard, the actual anatomical centres, were determined calculating the 2D distances between both positions ($\sqrt{BS^2 + CD^2}$). The mean absolute difference defines the accuracy (the agreement between the positions) of the guidelines, and the standard deviation (SD) of the absolute differences represents the precision (the repeatability of the procedure). The differences between the femoral centres according to the guidelines and the actual centres were also calculated for both BS and CD directions separately, with the mean differences resulting in the bias or error of the guidelines in both directions.

### Statistical analysis

Paired Student's *t* tests were applied to define whether the positions according to the guidelines differ significantly from the actual anatomical centres and to determine significant differences between the accuracies of both guidelines. $P < 0.05$ was set as significance level. Using the mean value and standard deviation of the actual anatomical ACL centre in deep–shallow direction (Table 2) and the number of 12 specimens, a post hoc power analysis was performed, resulting in a power of 0.79 detecting a significant difference of 1.2 mm between the actual centres and the centres according to the guidelines.

## Results

The ACL insertion was found at the proximal half of the medial wall of the lateral condyle, following the cartilage edge, often with a small part of the AM bundle positioned in the notch roof. The line dividing the ACL into an AM and PL part mostly ran parallel to Blumensaat's line. This radiographic line was on average 47.8 ± 3.5 mm, and the condyle

**Table 2** Absolute positions (mm) of the actual anatomical centres of the ACL, AM and PL in the 12 femora of the current study and the positions according to the guidelines of Luites et al. (2000) and Piefer et al. (2012) in deep–shallow at Blumensaat's line and in high–low direction at condyle depth

| | ACL | | | AM | | | PL | | |
|---|---|---|---|---|---|---|---|---|---|
| | Piefer et al. [38] | Luites et al. (2000) | Current study | Piefer et al. [38] | Luites et al. (2000) | Current study | Piefer et al. [38] | Luites et al. (2000) | Current study |
| Deep–shallow at BS | 14.0† (1.3) | 11.5 (1.1) | 12.2 (1.7) | 10.5† (1.0) | 10.3† (1.0) | 11.4 (1.7) | 15.7† (1.5) | 13.0 (1.2) | 12.3 (1.7) |
| High–low at CD | 8.7† (0.5) | 8.0 (0.5) | 7.9 (1.2) | 5.7† (0.3) | 4.8† (0.3) | 3.8 (1.5) | 12.1† (0.7) | 10.5 (0.6) | 9.5 (1.6) |

† $P < 0.05$ relative to actual anatomical centres in the current study

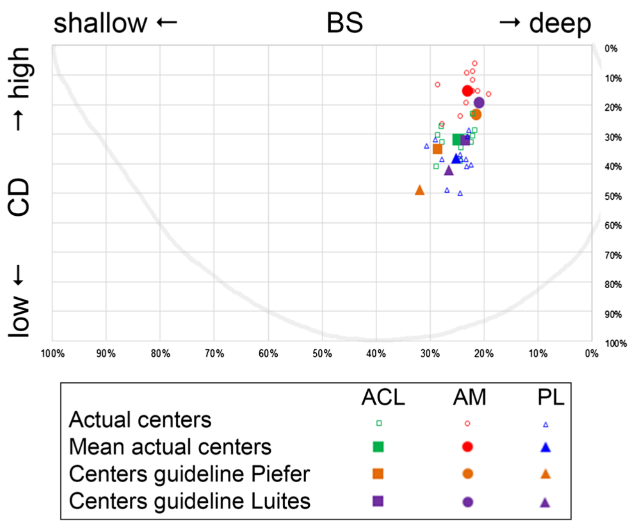


**Fig. 2** Relative positions of the actual ACL, AM and PL centres in the 12 femora ('gold standard') and their means. The guidelines according to Piefer et al. [38] and Luites et al. (2000) for ACL, AM and PL are also displayed. The *grey line* represents the average outline of a condyle

depth measured was 24.8 ± 1.5 mm. The dimensions of the femora from the present study did not differ significantly from the dimensions of the femora measured in 2000.

The actual ACL centre was found at an average of 12.2 ± 1.7 mm of Blumensaat's line and at 7.9 ± 1.2 mm of the condyle depth. The actual AM centre was situated at 11.4 ± 1.7 mm (BS) and 3.8 ± 1.5 mm (CD); the actual PL centre was situated at 12.3 ± 1.7 mm (BS) and 9.5 ± 1.6 mm (Table 2; Fig. 2). The calculated results applying Piefer et al's guidelines differed significantly at both dimensions for all centres from the actual centres found in this study. The calculated results with Luites et al's guidelines only differed significantly for the AM centre position in both directions from the actual centres (Table 2).

## Accuracy

The accuracies of the guidelines for the centres according to Piefer et al. represented by the absolute 2D distances, were 2.4 mm for the ACL centre, 2.7 for the AM centre and 4.6 mm for the PL centre (Table 3; Fig. 3). The calculated position of the AM centre was on average the most accurate result in deep–shallow direction (1.1 mm), the ACL in high–low direction (1.2 mm). The results for the PL centres were least accurate (2.7 mm in DS and 3.3 mm in HL), little worse than for the ACL, with the highest accuracy in deep–shallow direction. The worst results for the individual femora ranged between 3.2 mm (ACL in HL) and 6.7 mm (PL 2D). The bias of Piefer et al's guideline showed errors between −0.3 mm for the PL in shallow direction at BS and 0.8 mm for AM in deep direction at BS.

The accuracy of the guidelines for the centres according to Luites et al. (2000) ranged between 1.6 mm for the ACL centre and 2.2 mm for both AM and PL centres regarding the 2D distances (Table 3; Fig. 3). The position of ACL centre was most accurate, as well in high–low direction (0.9 mm) as in deep–shallow direction (1.1 mm). The accuracies for AM and PL centres were in both directions similar to each other: in deep–shallow direction 1.2 mm for AM and 1.3 mm for PL and in high–low direction 1.5 mm (AM) and 1.6 mm (PL). The worst individual results ranged between 2.2 mm (PL in DS) and 4.0 mm (AM 2D). The bias for guidelines of Luites et al. (2000) ranged between −1.0 mm for the AM in low direction at CD and 1.1 mm for the AM in deep direction at BS.

The results of the applied guidelines for the centre positions according to Luites et al. (2000) were more accurate than those of Piefer et al. for all measurements, except for the AM positions in deep–shallow direction on Blumensaat's line (Table 3; Fig. 3). The differences in outcomes between Piefer et al. and Luites et al. were significant for the PL centre in both directions (1.2 mm in HL and 2.0 mm in DS) and 2D (2.4 mm) and the AM position in high–low direction at the condyle depth (0.7 mm) and 2D (0.5 mm). The differences for the ACL centre, 0.3 mm (HL), 0.7 mm (DS) and 0.8 (2D), were not significant. The deep–shallow AM position according to Piefer et al. was significantly more accurate than that with Luites et al' guidelines, 1.1

**Table 3** Accuracy, precision [between '(..)'], bias and standard deviation [between '(..)'] and range [between '(..)'] in mm of the results applying the guidelines according to Piefer et al. (2012) and Luites et al. (2000) in deep–shallow direction at Blumensaat's line (BS) and high–low direction at condyle depth (CD)

| | | ACL | | | AM | | | PL | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Piefer et al. [38] | Luites et al. (2000) | P value† | Piefer et al. [38] | Luites et al. (2000) | P value† | Piefer et al. [38] | Luites et al. (2000) | P value† |
| Deep–shallow at BS | Accuracy (precision) | 1.8 (1.3) | 1.1 (1.0) | 0.285 | 1.1 (1.2) | 1.2 (1.2) | 0.001 | 3.3 (1.4) | 1.3 (0.6) | <0.001 |
| | Bias (SD) | −1.8 (1.4) | 0.7 (1.3) | n.s. | 0.8 (1.3) | 1.1 (1.3) | | −3.3 (1.4) | −0.7 (1.3) | |
| | Range | [0.0–3.4] | [0.0–2.8] | | [0.1–3.5] | [0.1–3.7] | | [0.7–5.1] | [0.2–2.2] | |
| High–low at CD | Accuracy (precision) | 1.2 (0.8) | 0.9 (0.8) | 0.285 | 1.1 (1.2) | 1.2 (1.2) | 0.011 | 2.7 (1.5) | 1.6 (1.0) | 0.010 |
| | Bias (SD) | −0.8 (1.2) | −0.1 (1.2) | n.s. | −2.0 (1.4) | −1.0 (1.4) | | −2.7 (1.6) | −1.0 (1.5) | |
| | Range | [0.2–3.2] | [0.1–2.4] | | [0.2–4.2] | [0.2–4.2] | | [0.0–5.0] | [0.3–3.3] | |
| 2D | Accuracy (precision) | 2.4 (1.1) | 1.6 (1.0) | 0.128. | 2.7 (1.0) | 2.2 (1.1) | 0.009 | 4.6 (1.2) | 2.2 (0.8) | <0.001 |
| | Range | [0.8–4.6] | [0.4–3.5] | n.s | [1.2–4.3] | [1.0–4.0] | | [2.6–6.7] | [1.2–3.8] | |

† *P* value: paired *t* test between the absolute differences of Piefer and Luites

*n.s.* not significant

versus 1.2 mm, respectively, however, a clinically not relevant difference.

The results for precision and repeatability were nearly similar in both groups ranging from 0.6 to 1.5 mm.

## Discussion

Many studies have reported the radiological positions of the anatomical centres of the ACL and its two functional bundles, the AM and PL bundles. This resulted in various guidelines for anatomical tunnel positioning and postoperative tunnel placement evaluation. In this article, we applied two sets of guidelines to get an impression of the variability of the accuracy. The most important finding of the present study was the inaccuracy of the averaged guidelines reported by Piefer et al. [38], which were composed through a meta-analysis of the data of various studies. The averaged guidelines were less accurate in the specimens used in the current study, compared to the guidelines of Luites et al. (2000), a single study. Piefer et al's guidelines were least accurate for the PL centre, with maximum errors of 5–6.7 mm.

Piefer et al. combined studies with large differences in outcomes in his guideline. These different outcomes in the various included studies, can be the result of the use of different methods and specimens [26]. Some included studies determined the centres of the insertion sites [6, 15, 39, 45, 49]; these were defined as the measured geometrical centre of the marked insertion site [15] (and current study), the 'parallel projection' of the central fibres of the bundle onto its attachment [6], the centre of the oval shape, determined by the software, which approximated the margins of the ACL footprint [45] or the centre chosen by 'vision' [39, 49]. Other studies included by Piefer et al. drilled tunnels and measured the positions of the tunnel centres [13, 18]. The imaging techniques on which the quadrant method was applied, varied from radiographs [15, 39, 49] to CT scans [13] and digital photographs [45]. Although Musahl et al. [35] found no significant difference between measurements on radiographs and CT scans, Jenny et al. [21] addressed different locations of the femoral ACL attachments according to the measurement technique (radiographs or CT scan). The presence of the variations could also be explained by the dissection technique: the separation of the ACL into two bundles and the determination of the attachment margins. All studies included by Piefer et al. report identical separation techniques of the AM and PL bundles based on identified differences in tension patterns during the complete range of knee motion. However, the ACL consists of many small fibres, and macroscopically separation is difficult and subjected to human error and bias [18]. The determination of the attachment margins differs in the various studies. As noticed in many anatomical studies, the fibres of the femoral attachment fan out over a broad flattened area [3, 12, 33, 34]. Some studies narrow the insertion to the area of the midsubstance fibres, the direct insertion [6, 24, 33, 44], while others, including the present study, use the entire broad attachment area, the direct and indirect insertion (Fig. 4). Recent publications describe this phenomenon [19, 20, 32, 41]. The main reason we chose for the entire attachment area is that the ligament insertion site and the underlying bone are additional parts of the ligament unit which functions as one complex, contributing to the constraining function of the ligament [23]. The ligamentous tissue is mediated by

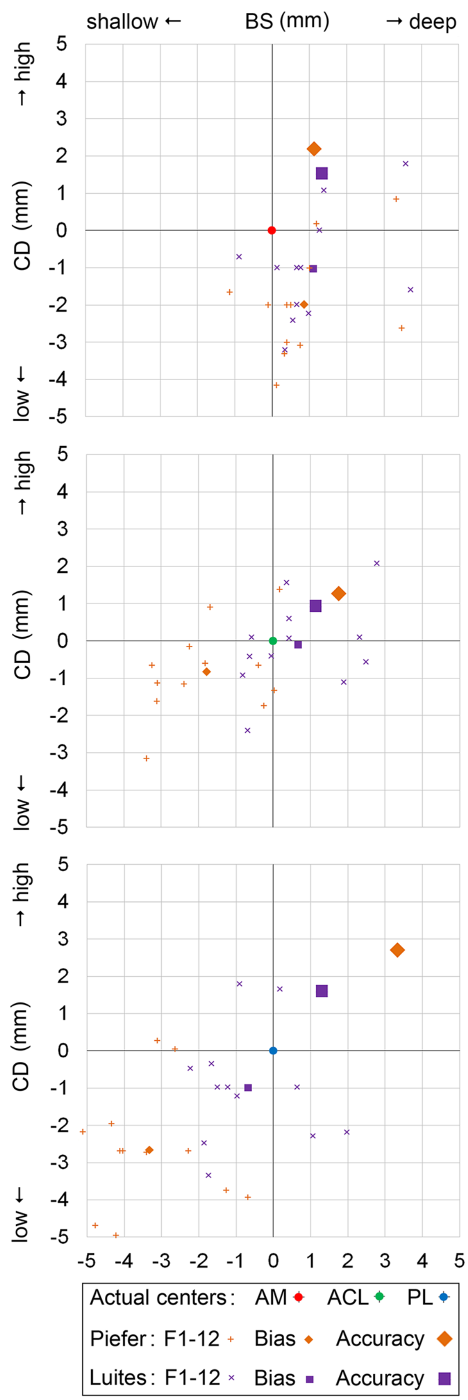


**Fig. 3** Positions of the individual centres applying the guideline sets of Piefer et al. [38] and Luites et al. (2000) relative to the actual anatomical centres (0,0) in the 12 femora for AM (*upper graph*), ACL (*central graph*) and PL (*graph at the bottom*); the mean difference in positions reflects the bias; the mean absolute difference in positions represents the accuracy

a transitional zone of fibrocartilage and mineralized fibrocartilage to that of rigid bone [3], which cannot be separated macroscopically [20, 41]. In daily practice, surgeons can choose for a different concept when deciding upon the femoral tunnel location. However, when using the averaged guidelines of Piefer et al., it is not clear which concept these values represent. In conclusion, the results of this study show the inaccuracy of the averaging method proposed by Piefer et al. Application of this method for anatomical ACL reconstruction will result in inaccurate femoral tunnel positioning.

Besides the exploration of the causes of the variability of outcomes as stated above, another important question to answer is which magnitude of inaccuracy on tunnel placement has any clinical effect on knee stability. Several studies have shown the influence of different femoral tunnel positions on biomechanical parameters in cadaveric knees [29, 31, 36, 50]. Musahl et al. [36] showed significant different anterior tibial translation values between two tunnel positions, at 25 % × BS/40 % × CD and at 38 % × BS/8 % × CD, with an inter-distance of approximately 9 mm. Zavras et al. [50] demonstrated a large effect on the anterior–posterior (AP) laxity of the knee varying the femoral graft position with 3 mm. This effect was mainly in the positions 3 mm towards posterior (deeper in the notch along the notch roof) and 3 mm towards the 12 o'clock position (higher) from the isometric point, defined as 3 mm distal to the posterior edge of Blumensaat's line at 10:30–11:00 o'clock, which is in the proximal edge of the femoral attachment. Other studies compared tunnels at the 11 o'clock and 10 o'clock positions [29, 31, 42]. Assuming a clock with the 12 o'clock (noon) position defined as the top of the intercondylar notch and the 6 o'clock defined as the bottom of the lateral femoral condyle in the flexion position [33] and a height of circa 20 mm [7], both positions are approximately 3–4 mm located from each other. Markolf et al. [31] tested AP laxity with tunnels at different clock positions, adapting the graft pretension at the same time. He showed that tunnels positioned towards 10 o'clock and 12 o'clock showed no significant different AP laxities of the knee relative to a standard 11 o'clock tunnel, which was located 6–7 mm anterior to the posterior wall. However, a tunnel positioned 5 mm more shallow, anterior along the notch roof in the direction of Blumensaat's line, had significantly different AP laxity in most knee angles compared to the 11 o'clock tunnel. Tunnels positioned 2.5 mm posterior (deeper), showed no significantly different AP laxities. Loh et al. [29] tested the anterior tibial translation with tunnels at 10 and 11 o'clock positioned with a 7-mm offset drill guide, resulting in smaller, not significant, anterior translation in the lower flexion angles for the 10 o'clock tunnel.

Summarizing the results of these biomechanical studies, it can be estimated that a positioning error at the femoral condyle beyond 3–4 mm can result in a different biomechanical behaviour, although this is not similar for the entire area and for deviations in each directions. Application of this reasoned threshold of 3 mm, results in the findings of Table 4, showing that in 92 % of the femora

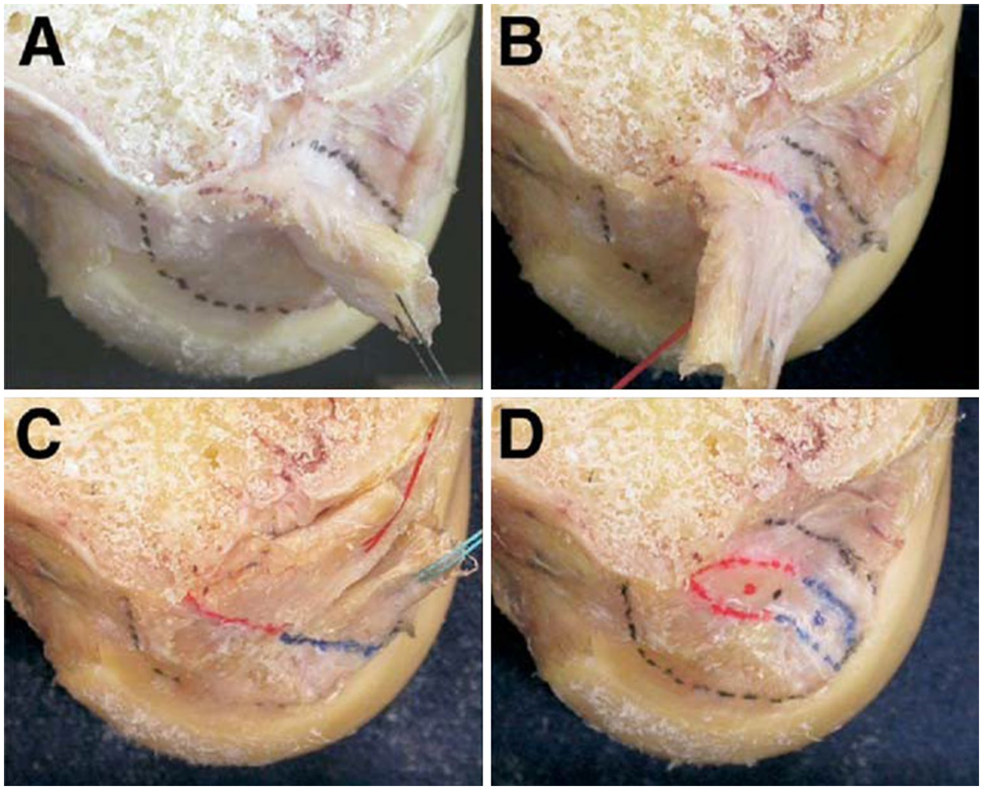


**Fig. 4** At these pictures from Mochizuki et al. [33], the difference between the direct and indirect insertion is clearly visualized. The direct insertion consists of the midsubstance fibres; the indirect insertion consists of the fibres fanning out into the bone of the intercondylar notch

**Table 4** Number of femora (%) with tunnel positions according to the guidelines of Piefer et al. (2012) and Luites et al. (2000) with a deviation over 3 mm from the actual anatomical centre

| | ACL | | AM | | PL | |
|---|---|---|---|---|---|---|
| | Piefer et al. [38] | Luites et al. (2000) | Piefer et al. [38] | Luites et al. (2000) | Piefer et al. [38] | Luites et al. (2000) |
| Deep–shallow at BS | 4 (33 %) | 0 | 2 (17 %) | 0 | 8 (67 %) | 2 (17 %) |
| High–low at CD | 1 (8 %) | 0 | 4 (33 %) | 1 (8 %) | 4 (33 %) | 1 (8 %) |
| 2D | 4 (33 %) | 1 (8 %) | 6 (50 %) | 2 (17 %) | 11 (92 %) | 3 (25 %) |

the guidelines according to Piefer et al. result in PL tunnel positions deviating more than 3 mm from the PL actual centre. This could possibly result in different biomechanical behaviours in these knees as aimed for regarding the PL tunnel positioning. Furthermore, the table also shows that the guidelines for the PL bundle from Luites et al. (2000) will result in 25 % of the femora with errors beyond the threshold of 3 mm. However, it remains unclear what influence the amount of such an inaccuracy has on the clinical outcome.

Although femoral graft positions in ACL literature are mentioned as an important factor in clinical outcome, various clinical studies could not evidently show differences in post-operative biomechanical tests (Lachman and pivot-shift test) caused by small variations in femoral tunnel positions [22, 42]. Seon et al. [42] showed in a clinical study that the intra-operative internal rotation was significantly better (2°) for the lower 10 o'clock tunnel relative to the higher 11 o'clock tunnel; however, this did not result in a reduction in the residual pivot-shift phenomenon 2 years post-operative, suggesting the found difference was not clinically relevant in terms of functional activities. However, the tunnel positions in this study were not objectively and accurately measured post-operative, a limitation indicated by van Eck et al. about both clinical [9] and cadaveric studies concerning femoral tunnel positions [8]. Besides that, many other factors, not only concerning surgical techniques, play a role in clinical outcome. Hence, the influence of various positions of the femoral tunnel on clinical parameters remains uncertain. Besides that, the final quest for the optimal femoral tunnel position combined with the optimal position technique and measurement method remains.

This study has several limitations. Although the measurements of the ACL centres of the specimens in the current study were performed by another researcher, the dissections were done by the same researcher (JL). This can be judged as a limitation, besides the observation that it could be an explanation for the similarities between the results from the study in 2000 and this study and may emphasize the influence of dissection choice regarding the attachment margins at the geometrical insertion results. The dissection was performed by macroscopic evaluation. Other limitations are related to the specimen: we performed the measurements on a limited number of femora, which were embalmed and probably of older age than patients undergoing ACL reconstruction. However, the used specimen had no osteoarthritic changes. Despite the limitations, the anatomical results [30] and radiological results are in line with the literature [5, 39, 45].

## Conclusion

The current study shows that combining the various results of femoral centre positions from different radiographic studies using different concepts and techniques, does not lead to accurate guidelines for individual tunnel positioning.

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