

Variability of landmark acquisition affects tunnel calculation in image-free ACL navigation

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Abstract

Purpose The purpose of this study was to determine the inter- and intraobserver variability of intraarticular landmark identification for tunnel position calculation in image-free anterior cruciate ligament (ACL) navigation.

Methods In a test/retest scenario, thirteen experienced ACL surgeons (>50 reconstructions year) experienced in image-free ACL navigation were asked to identify the landmarks required for image-free ACL navigation in the same cadaver knee. Landmark positions were registered using a fluoroscopic ACL navigation system. Positions were determined using validated radiological measurement methods. For variability analysis, mean positions, deviations between the test/retest positions, standard deviations (SD) and range were calculated.

Results Interobserver analysis showed a mean variability (SD) for the tibial landmark positions of 3.0 mm with deviations of up to 24.3 mm (range). Mean femoral landmark variability was 2.9 mm (SD) with deviations of up to 11.3 mm (range). Intraobserver analysis showed a tibial reproducibility of 2.2 mm (SD 2.0 mm; range 10.9 mm) and a femoral of 1.9 mm (SD 1.9 mm; range 10.4 mm).

Conclusion The data of the presented study suggest that a considerable inter- and intraobserver variability in intraarticular landmark identification exists. Reasonable ranges were found that have to be considered as a potential risk for miscalculation of tunnel positions in image-free ACL reconstruction.

Clinical relevance Landmark acquisition affects tunnel calculation in image-free ACL.

Level of evidence IV.

Keywords ACL · Tunnel positions · Navigation · Variability · Landmark acquisition

Introduction

Despite increasing knowledge about knee anatomy and biomechanics as well as technical improvements in ACL reconstruction, tunnel misplacement is still one of the most common reasons for graft failure after anterior cruciate ligament (ACL) reconstruction [9, 14, 15, 19, 42, 45]. Radiological studies indicate that approximately 10–40 % of drill holes in primary ACL reconstructions have been incorrectly placed and that tunnel misplacement highly correlates with poor results after ACL reconstruction [6, 10, 12, 14, 17, 19, 28, 36].

Although the importance of correct tunnel positioning is well accepted and there is general agreement that tunnel positions within the anatomical insertion areas of the ACL are fundamental to successful ACL reconstruction and long-term stability [2, 19, 24, 27, 47], the implementation of this knowledge into intraoperative tunnel positioning seems to remain difficult since reliable landmarks, allowing correct tunnel identification, do not consistently exist [8, 13, 20, 29, 31, 32, 38, 40, 44].

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To improve reproducibility and accuracy of anatomical tunnel positioning, navigation technology was introduced to ACL reconstruction. Based on pre-/intraoperative image acquisition (image-based systems) or on intraarticular landmark acquisition (image-free systems), these systems enable the surgeon to plan, identify and drill optimal tunnel positions, to check isometry, to perform a virtual impingement analyse and to measure anterior tibia translation and rotational stability [18, 20, 21, 23, 25, 29, 39, 43, 46]. Depending on the surgeon's preferred reconstruction technique, navigation systems allow for transtibial and anteromedial portal techniques as well as for single- and double-bundle reconstruction.

Studies on image-free ACL navigation indicate the feasibility of image-free ACL navigation. Other studies have shown that image-free ACL navigation enables for reliable translation and rotation measurements as well as for isometry analysis [3, 5, 16, 21, 22, 25, 26, 29, 30, 33]. Thus, the reliability (accuracy and reproducibility) of tunnel planning has never been validated.

For tunnel position planning, the software of image-free navigation systems [11, 16, 21, 25, 33, 43] creates a 3D model of the knee joint. Therefore, the system requires the acquisition of intraarticular landmarks and surfaces. Based on kinematic analysis and the identification of special landmarks and areas, such as the medial tubercle spine, the anterior margin of the posterior cruciate ligament (PCL), the anterior horn of the lateral meniscus and the o'clock positions at the femur, a software algorithm calculates and suggests an optimized anatomical and isometric tunnel positions.

Since the quality of the calculated 3D model and the suggested tunnel positions strongly rely on the reproducibility and accuracy of intraarticular landmark identification, there obviously seems to be a reasonable potential for miscalculation. Consequently, one wrong landmark, as well as many not very precise acquired landmarks, could create wrong 3D models suggesting wrong tunnel positions.

Therefore, the aim of this study was to determine the inter- and intraobserver variability of intraarticular landmark identification in navigated ACL reconstruction. The hypothesis of this study was that intraarticular landmark identification has a reasonable variability, which has to be considered in image-free ACL navigation.

Materials and methods

This study was performed in one fresh female cadaver knee, in which all ligaments were intact before intervention. The study was performed, imitating an operating room (OR) situation. After positioning of the cadaver and

draping the leg in an OR like way, the endoscope (Smith & Nephew, Andover, MA) was introduced over a standard anterolateral portal. Then the ACL was cut in its midsubstance over a deep anteromedial portal with a punch, and the fibres were then removed with a shaver. At the tibia, the stump of the ACL was resected in a way that the tibial insertion area of the ACL could be clearly identified. At the femur, the ACL fibres were removed to a degree that the insertion area at the lateral notch wall could be clearly identified. Further soft tissue resection was performed, so that the surgeons could clearly identify the anterior horns of both menisci, the transverse ligament, the medial tubercle spine and the PCL as well as the over the top position and the inner notch wall geometry.

Navigation system

For later analysis, a fluoroscopic-based ACL navigation system (Brainlab, Feldkirchen, Germany) was used [39]. Therefore, one bicortical Schanz Screw (5 mm) was fixed at the distal lateral femur and the distal medial third of the tibia. Further, a metal scaling ball was fixed to the knee, to allow for later measurement of the positions. Next, dynamic reference bases (DRB's) containing light emitting diodes (LEDs) were rigidly fixed at the Schanz screws. Fluoroscopic images in ap and lateral projections were then obtained using a standard fluoroscope (Ziehm, Nürnberg, Exposcop 7000) which was connected to a registration kit, containing LED's. During image acquisition, an optoelectronic Polaris® camera (NDI Polaris, Waterloo, Canada) overlooking the surgical field, digitized the reflecting infrared flashes from the DRB's and the registration kit, creating an individual infrared reflection image. The software of the navigation system used the fluoro image and the LED informations to calculate the three-dimensional position of the knee. Using navigated instruments, intra- and extraarticular landmarks, positions and surface could precisely been tracked and displayed on the fluoroscopic images throughout the operation.

Surgical procedure

Thirteen experienced ACL surgeons (>50 reconstructions year) trained in image-free ACL reconstruction were asked to identify the specific intraarticular landmarks required for image-free ACL navigation in the same knee under the same OR like conditions. According to the workflow of image-free ACL navigation [21, 25], one surgeon after the other had to identify the above-mentioned landmarks arthroscopically using a navigated palpation hook. The display of the navigation system was blinded for the surgeons. As in image-free navigation, they had to position the tip of the navigation hook on the identified landmarks. Of

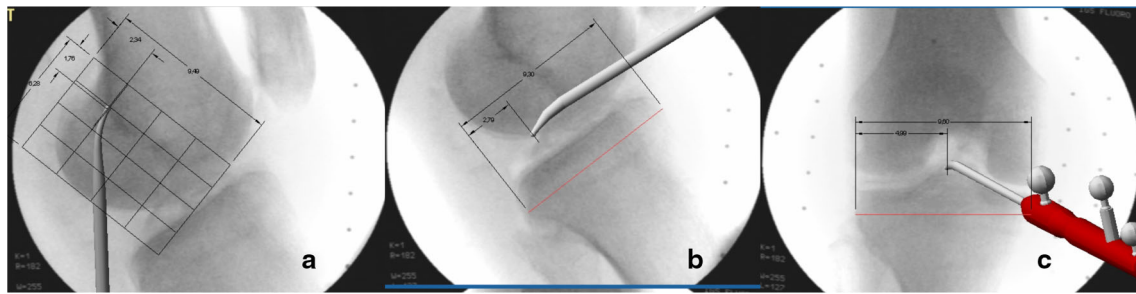


Fig. 1 Measurement of the landmark positions. **a** Measurement of the femoral landmark position using the quadrant method to determine the height and depth of the identified landmark. **b** and

c Measurement of the identified tibial landmark position using Staubli's radiographic measurement method

each identified landmark (landmark 1: anterior horn of the lateral meniscus; landmark 2: medial tubercle spine; landmark 3: anterior border of the PCL; landmark 4: 12 o'clock position; landmark 5: 10:30 o'clock position), screenshots of the identified position were taken. Using a fluoroscopic-based navigation system, the positions were indicated in the referenced fluoroscopic anterior–posterior (ap) and lateral projections. A retest for intraobserver analysis was performed, approximately four hours later.

Measurement of the landmark positions

All screenshot images of all surgeons, identifying the above-mentioned landmark positions, were transferred into a professional CAD drawing and measurement software (Canvas 9.0, ACD Systems). To determine the position and to measure deviations and variability of the different landmark positions, reliable radiological measurement methods were used. At the femur, Bernard and Hertel's quadrant method and Staubli's method for the tibial measurement were used (Fig. 1).

For femoral analysis, a quadrant was projected on the overlapping condyles of the femur according to the method of Bernard and Hertel [4]. The quadrant was positioned so that the proximal line was overlapping Blumensaat's line, the projection of the intercondylar roof in lateral X-rays. The total sagittal depth and total height of the intercondylar surface determined the size of the quadrant.

According to the femur, tibial measurement followed in relation to a line described by Staubli [41]. In the lateral radiograph, a line was drawn parallel to the sagittal tibial joint line. The length of the line is limited ventrally by the tibial cortex and dorsally by the descending eminentia intercondylaris.

Then, the different positions of each landmark were measured along the femoral quadrant and the tibial line using a calibrated measurement tool. With the metal scaling ball, all acquired positions of the different landmarks could be determined in millimetres and were collected in

an excel data sheet for further analysis. Data were collected in an excel (Microsoft Excel 14.2.5, USA) data sheet. The Study was approved by the local ethics committee of the university of cologne.

Statistical analysis

For both, tibial and femoral analysis, mean positions of each landmark were calculated in two planes to describe their three-dimensional position. The variability of each landmark was then analysed by calculating the standard deviations (SD) of the mean positions in two planes. Further the range between the different landmark positions was calculated, indicating outliers. The variability of the tibial and femoral landmark identification was calculated by calculating the mean SD for the three tibial and the two femoral landmarks. For determination of the reproducibility (intraobserver analysis) of the landmark identification, the differences between the positions of the test and retest were calculated for each landmark of each surgeon in two planes. Further SD and range were calculated to determine outliers.

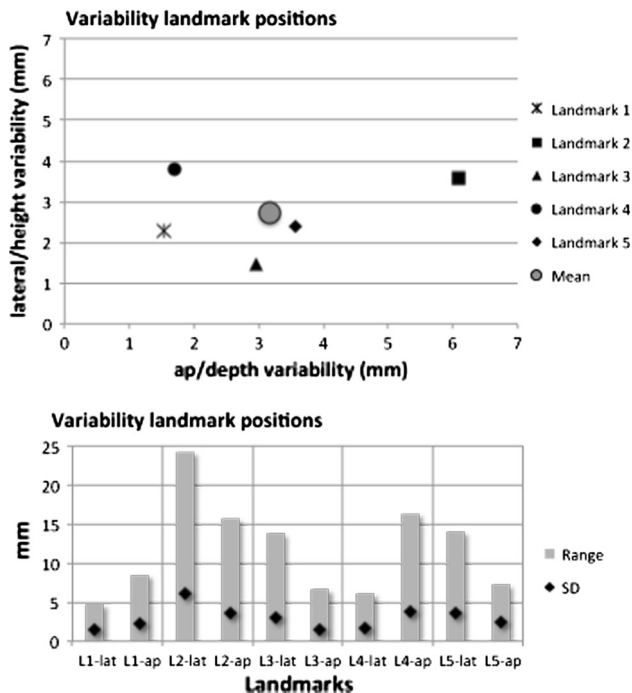
Results

Interobserver results (Table 1)

The interobserver analysis showed a mean variability of 3.0 mm for the tibial and 2.9 mm for the femoral landmarks. Different variability results were found in the statistical analysis between the five landmarks (Figs. 2, 3). Landmark 1, the anterior horn of the lateral meniscus, showed the lowest variability results with 1.9 mm and also the lowest range of 6.6 mm, indicating the highest accuracy of the five landmarks. In contrast, landmark 2, the medial tubercle spine, showed the highest variability of the required landmarks for image-free ACL navigation. Deviations of 4.8 mm and a range of up to 20.1 mm were found

Table 1 Interobserver variability of the acquired landmark positions (mm)

| Interobserver variability—Landmark positions (mm) | | | | | | | | | | | | | | | | |
|---|--|------|------|-------------------------------------|------|------|-----------------------------------|------|------|------------------------|--------|------|--------------------------|--------|------|--|
| | Landmark 1 Anterior horn lateral meniscus | | | Landmark 2 Medial tubercle spine | | | Landmark 3 Anterior border PCL | | | Landmark 4 10:30 | | | Landmark 5 12 o'clock | | | |
| | lateral | ap | mean | lateral | ap | mean | lateral | ap | mean | depth | height | mean | depth | height | mean | |
| Mean | 28.7 | 26.0 | – | 22.4 | 38.3 | – | 10.2 | 32.0 | – | 10.7 | 7.9 | – | 13.9 | 10.9 | – | |
| SD | 1.5 | 2.3 | 1.9 | 6.1 | 3.6 | 4.8 | 3.0 | 1.5 | 2.2 | 1.7 | 3.8 | 2.8 | 3.6 | 2.4 | 3.0 | |
| Range | 4.7 | 8.5 | 6.6 | 24.3 | 15.8 | 20.1 | 13.8 | 6.6 | 10.2 | 6.1 | 16.4 | 11.3 | 14.1 | 7.3 | 10.7 | |
| Mean | tibial landmarks: 3.0 | | | | | | | | | femoral landmarks: 2.9 | | | | | | |

**Fig. 2** Variability of landmark positions

for landmark 2. Landmark 3 (anterior border of the PCL), landmark 4 (12 o'clock position) and landmark 5 (10:30 o'clock position) showed variability results between 2.2 and 3.0 mm with ranges of 10.2–11.3 mm.

Intraobserver results (Table 2)

The intraobserver analysis showed mean deviations of 2.2 mm and 1.9 mm between the test and retest's positions of the tibia and the femur, with ranges of up to 10.9 mm. Deviations between the positions were found in the ap as well as in the lateral plane (Fig. 4).

Mean deviations of 1.8 mm (SD 1.7; range 6.3 mm) for landmark 1, 2.9 mm (SD 2.1; range 7.3) for landmark 2 and 1.9 mm (SD 2.3; range 10.9) for landmark 3 were found for the tibia. At the femur, mean deviations of

1.7 mm (SD 2.2; range 10.4) were found for landmark 4 and 2.2 mm (SD 1.9; range 7.1) for landmark 5.

Discussion

The most important finding of the presented study is that a considerable inter- and intraobserver variability of intra-articular landmark identification exists. Therefore, the hypothesis of the presented study can be accepted. The variability of the intraarticular landmarks positions required in navigated ACL reconstruction to calculate the tunnel positions was found to be 1.9–4.8 mm. Intraobserver analysis showed a mean reproducibility of 1.8–2.9 mm. Next to the variability and reproducibility, ranges between 6.6 and 20.0 mm were found, indicating that outliers exist. The presented results therefore indicate that a considerable variability in landmark identification exists that may influence the calculation of tunnel positioning in image-free ACL navigation.

Thus, these results have to be critically discussed, since a reasonable number of studies seem to confirm the reliability of image-free ACL navigation systems [6, 7, 11, 21, 29].

Picard demonstrated in a study on “Navigated Anterior Cruciate Ligament Reconstruction: Radiographic Validation of a Nonimage-based System” that navigation resulted in more accurate tunnel placements compared to traditional arthroscopic techniques. Thus, in this study, tunnel planning was performed according to the surgeons desired and indicated location by preoperatively inserting radiopaque fiducials [29]. Since tunnel positions were planned by the surgeon and not by the navigation system, the validation of Picard's study is limited to the accuracy of the navigated drilling process.

A more recent validation study on image-free ACL navigation compared the navigated measurement and determination of tunnel positions with radiological measurement methods of tunnel positions. In this study, the tibial and femoral tunnel positions were “placed into the

Fig. 3 Variability of landmark identification

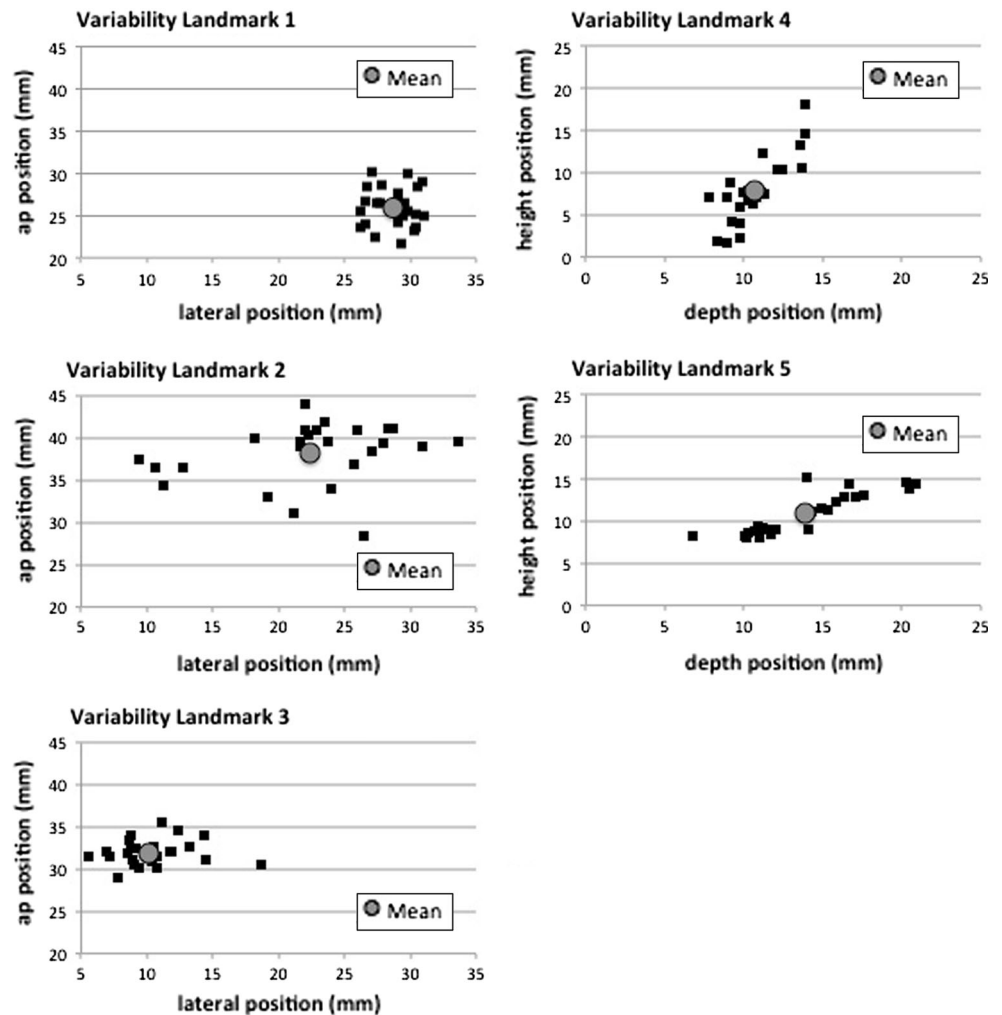


Table 2 - Intraobserver deviations between the test/retest landmark positions (mm)

| Intraobserver landmark deviations (mm) | | | | | | | | | | | | | | | | |
|--|-----------------------|-----|-------------------------------------|---------|-----|-----------------------------------|---------|-----|---------------------|------------------------|--------|--------------------------|-------|--------|------|--|
| Landmark 1 Anterior horn lateral meniscus | | | Landmark 2 Medial tubercle spine | | | Landmark 3 Anterior border PCL | | | Landmark 4 10:30 | | | Landmark 5 12 o'clock | | | | |
| | lateral | ap | mean | lateral | ap | mean | lateral | ap | mean | depth | height | mean | depth | height | mean | |
| Mean | 1.6 | 2.0 | 1.8 | 2.8 | 3.0 | 2.9 | 2.2 | 1.5 | 1.9 | 1.0 | 2.3 | 1.7 | 2.5 | 1.9 | 2.2 | |
| SD | 1.4 | 2.0 | 1.7 | 1.8 | 2.5 | 2.1 | 2.9 | 1.5 | 2.3 | 1.1 | 2.9 | 2.2 | 2.2 | 1.5 | 1.9 | |
| Range | 4.3 | 6.3 | 6.3 | 6.0 | 7.3 | 7.3 | 10.9 | 4.7 | 10.9 | 3.4 | 10.4 | 10.4 | 7.1 | 3.9 | 7.1 | |
| Mean | tibial landmarks: 2.2 | | | | | | | | | femoral landmarks: 1.9 | | | | | | |

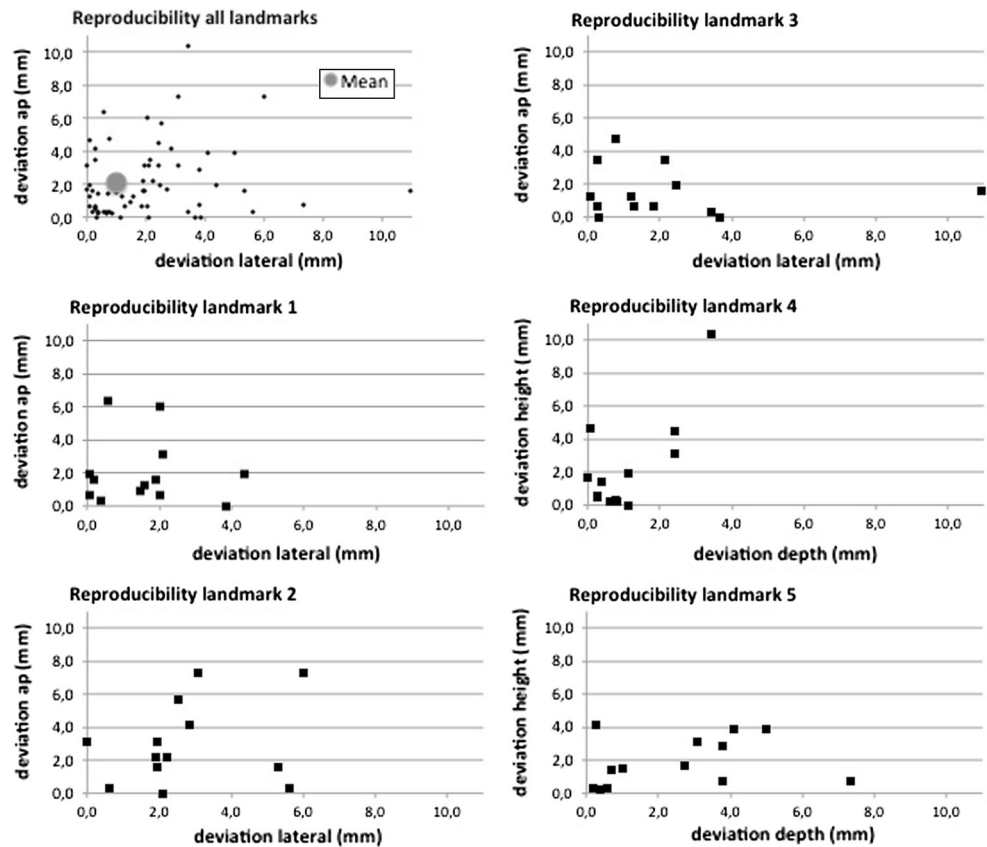
joint according to the surgeon’s judgment of the optimal location” [16]. Then, navigated and radiological measurements of these positions followed and both methods were compared. The validation of this study is therefore limited to a comparison between the two measurement methods. Tunnel planning did not follow the navigation protocol.

In a cadaver study, Plaweski et al. [33] compared the variability of conventional and image-free navigated tunnel

positions. The results of their qualitative analysis showed more anatomical tunnel positions in the navigated group; thus, a quantitative analysis of the tunnel positions was not performed.

Angelini et al. analysed the differences between conventional and navigated tunnel positions using isometry measurement methods [3]. Tunnel positions in the navigation group were calculated by the navigation system

Fig. 4 Test–retest deviations—reproducibility of landmark identification



according to the above-mentioned landmark acquisition. The navigation group showed significant better results concerning isometry. Tunnel positions, accuracy and reproducibility were not addressed in this study.

In a prospective, randomized, double-blind study, Hart et al. [11] compared stability results, IKDC and Lysholm score as well as radiological tunnel positions between navigated and conventional ACL reconstruction. There were no significant differences between both groups except for the variability of femoral tunnel positioning, which was smaller in the navigation group.

Schep et al. analysed the intraobserver variability between conventional and navigated tunnel positioning in ACL reconstruction. Their results showed that navigation can reduce the intraobserver variability compared to conventional ACL reconstruction. Thus, the intraobserver variability in the navigation group still showed reasonable deviations between the planned tunnel positions of 5 mm (SD 2.4; range 1.8–9.6 mm) at the tibia and 4.6 mm (SD 2.1; range 2.1–8.4 mm) at the femur [37]. Schep explained the variability of tunnel positions in the image-free ACL navigation group with several existing, different but appropriate tunnel positions.

Although different aspects, such as translation and rotation measurements as well as benefits related to

isometry analysis, have been validated and analysed, neither the above-mentioned studies [3, 5, 16, 21, 22, 25, 26, 29, 30, 33, 34] nor—to our best knowledge—other studies have so far analysed the variability of tunnel positions in image-free ACL navigation. Therefore, the results of the presented study have to be considered, discussing the accuracy and reliability of tunnel positioning in image-free ACL navigation. Corresponding results could be found in navigated total knee arthroplasty. However, navigation technology is accepted as a precise method to improve accuracy in navigated total knee arthroplasty, different studies report on limitations related to the variability of landmark identification. Determining a reasonable landmark identification variability in navigated total knee arthroplasty, Robinson et al. [35] concluded that the variability in landmark identification represents a source of method error. Beyond Amanatullah et al. [11] recently showed that deviations in landmark identification of more than 2 mm influence the precision and outcome in navigated total knee arthroplasty.

One of the main shortcomings of this study is that it was only possible to analyse the variability in one knee. Further, it was only possible to allow thirteen surgeons to identify the necessary landmarks. The number of surgeons was limited by the condition of the cadaver knee, which

had to be the same for all surgeons during the test and the retest. Therefore, also the statistical impact of the subgroup analysis is limited.

Finally, the results of the presented study addressed the variability of landmark identification in image-based ACL navigation. The variability of the calculated tunnel positions by image-free navigation systems was not analysed. Nevertheless, it is obvious that the variability of tunnel positions in image-free ACL navigation is influenced by the variability of the intraarticular landmark identification, since the tunnel positions are calculated based on an algorithm.

Conclusion

The results of the presented study indicate reasonable deviations for landmark identification in the inter- and intraobserver analysis that have to be considered as a certain potential for tunnel position miscalculation in image-free ACL navigation. Surgeon's applying image-free ACL reconstruction system's should therefore be aware that the reliability of tunnel positioning depends on the quality of information the systems receives.

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