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Critical parameters of tunnel positioning in ACL reconstruction: a retrospective MRI analysis

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Anterior cruciate ligament (ACL) rupture is one of the most common knee injuries requiring surgical intervention. The increasing number of revision surgeries indicates the potential presence of technical errors during primary reconstruction, emphasizing the importance of outcome analysis and careful surgical planning. MRI remains the gold standard not only for diagnosing ACL injuries and associated lesions, but also for evaluating postoperative changes. Objective. To assess MRI-based measurements of femoral and tibial tunnel inclination and entry point location as potential technical causes of ACL graft failure. Methods. A retrospective analysis was conducted on 105 knee MRI scans from patients following primary ACL reconstruction. The parameters evaluated included femoral and tibial tunnel inclination angles on coronal views, femoral tunnel entry point using a modified Bernhard and Hertel method, and tibial tunnel entry point assessed via the Amis and Jacob line. Results. A femoral tunnel angle within the 30°–50° range was found in 63 % of cases, with the optimal range of 32°–39° observed in 21 %. In 16 % of cases, the angle exceeded 50°, and in 3 % it was less than 17°. The femoral tunnel entry point fell within the normal range in 46 % of cases, while in 42 cases it was located outside the defined measurement rectangle. Tibial tunnel position on sagittal projection was anatomically correct in 38 % of cases, anteriorly displaced in 21 %, and posteriorly displaced in 41 %. The optimal tibial tunnel inclination angle (≥ 65°) was found in 61 % of cases. Graft integrity was preserved in 24 % of cases with posterior tibial tunnel positioning, and in only 6 % with anterior placement. Conclusions. Technical errors in tunnel formation are a common cause of ACL graft failure. Accurate determination of the tunnel entry point is the most critical factor, while tunnel angle plays a secondary, yet diagnostically valuable, role. These findings highlight the need for meticulous planning, including the use of MRI and intraoperative navigation techniques to optimize tunnel placement.

Розрив передньої схрещеної зв'язки (ПСЗ) — одна з найпоширеніших травм колінного суглоба. Зростання кількості ревізійних операцій свідчить про можливі технічні помилки під час первинної реконструкції, що актуалізує необхідність аналізу результатів і ретельного планування. Магнітно-резонансна томографія (МРТ) є «золотим стандартом» у діагностиці як розривів ПСЗ, так і супутніх ушкоджень, а також ефективним інструментом для вивчення післяопераційних змін. Мета. Оцінити показники нахилу та розташування феморального та тібіального каналів за допомогою МРТ для виявлення можливих технічних причин ушкодження трансплантата ПСЗ. Методи. Проведено ретроспективний аналіз 105 МРТ обстежень колінного суглоба в пацієнтів після первинної пластики ПСЗ. Вимірювались: кут нахилу феморального і тібіального каналів у коронарній проєкції, положення точки входу феморального каналу. Результати. Кут нахилу стегнового каналу в межах 30°–50° виявлено у 63 % випадків, оптимальні 32°–39° — у 21 %. У 16 % пацієнтів він перевищував 50°, у 3 — менше 17°. Точка входу феморального каналу відповідала нормі в 46 % осіб, у 42 випадках спостерігалося розташування феморального каналу поза межами вимірюваного прямокутника. Положення тібіального каналу на сагітальній проєкції зберігало анатомічну межу в 38 % обстежень; у 21 він був зміщений допереду, у 41 — дозаду. Кут нахилу тібіального каналу був оптимальним (≥ 65°) у 61 % випадків. За заднього розташування каналу трансплантат зберігався у 24 % випадків, за переднього — у 6. Висновки. Поширеність технічних помилок під час формування кісткових каналів може бути причиною ушкодження трансплантата. Найкритичнішим є правильне визначення точки входу каналів, тоді як кут нахилу відіграє другорядну роль, проте є маркером технічної похибки. Результати підкреслюють необхідність ретельного планування, зокрема з використанням МРТ і додаткових методик навігації під час операції. Ключові слова. Передня схрещена зв'язка, МРТ, кісткові канали, трансплантат.

Keywords. Anterior cruciate ligament (ACL), MRI, bone tunnels, graft

Introduction

Anterior cruciate ligament (ACL) rupture is the most common ligamentous injury in the knee. The annual incidence in the United States alone is approximately 1 in 3,500 individuals, requiring 400,000 ACL reconstructions annually [1]. Information is limited by the lack of any standard epidemiological surveillance mechanism in the general population and may be imprecise. Overall, available evidence suggests that the incidence of ACL ruptures has increased in patients of all ages over the past decades [2–10]. The incidence of revision reconstructions is also increasing [11]. Although the literature is not unanimous regarding the ability of ACL reconstruction to prevent post-traumatic osteoarthritis (OA), some studies have found evidence of improved stability and prevention of further meniscal and cartilage damage after ACL reconstruction [12–14]. The frequency of revision reconstruction of the ACL (RRACL) ranges from 6–12 % according to some authors [15] to 20–25 % [16, 17] by others.

RRACL leads to worse functional outcomes than primary (PRACL) [18]. Additional problems associated with revision include prolonged recovery time, longer disability, and higher economic costs, especially in the case of 2-stage revisions. Therefore, the issue of planning revision reconstruction and the possibility of performing a single-stage revision is important, as this technique leads to better outcomes [19–21].

In ACL injuries, imaging with magnetic resonance imaging (MRI) is a high-quality tool for confirming the injury and diagnosing concomitant injuries. However, MRI is also useful for determining postoperative changes after a previous PRACL and for planning further RRACL.

Purpose: to determine the main indicators that can be detected on magnetic resonance imaging for planning further treatment tactics in patients with graft damage, as well as to analyze the technical factors that lead to its damage.

Material and Methods

The results of MRI examinations in patients with previously performed PRACL were analyzed. The examination was carried out on the basis of the "Diagnostic Center M24", Kyiv from 2014 to 2024. The study was performed in compliance with ethical principles, including the provisions of the Declaration of Helsinki (2000) and relevant legislation of Ukraine.

The work is based exclusively on anonymized MRI data obtained in compliance with ethical requirements and without the possibility of identifying individuals. A total of 105 MRI examinations of patients with primary ACL reconstruction and unsatisfactory, according to MRI data, results in terms of graft integration were studied. The age of the patients was (36 ± 1) years. The study protocol included MRI images, as well as MRI examination findings. The following were measured: the angle of inclination of the femoral and tibial canals in the coronal projection, the position of the femoral canal entry point according to the adapted Bernhard and Hertel method, the tibial canal entry point according to the Amis and Jacob line. All calculations were performed using MRI viewing software (RadiAnt DICOM Viewer). The measurements were entered into an Excel spreadsheet, after which statistical analysis of the data was performed. Additionally, the angle of inclination of the lateral plateau, the area of the femoral fossa, migration and failure of fixators, and concomitant meniscal injuries were determined.

Coronal projection, angle of inclination of the femoral canal

In anatomic single-bundle reconstruction of the ACL, the femoral tunnel should be located at the site of attachment of the native ACL. The correct location of the tunnel entry point and its inclination are of fundamental importance for the best clinical outcome. The optimal angle of inclination in direct projection in various sources is considered to be about 32°–39° [22, 23]. It provides sufficient length of the channel for fixation of the ligament, but an angle less than 32° is also acceptable. But it should be remembered that the longer the channel, the greater the likelihood of its expansion after surgery, which can lead to instability of the graft and its integration. Also, the angle of inclination of the channel may indirectly indicate an incorrectly determined entry point. An angle less than 17° may cause verticalization of the ligament and, accordingly, instability.

Too sharp an angle may lead to insufficient length of the channel for fixation of the ligament. The measurement was performed in the coronal projection, on the slice with the most optimal visualization of the canal, between the line drawn through the middle of the femoral diaphysis and the line drawn through the femoral tunnel.

A range of 30° to 50° can be considered a good result. In the study, the angle of inclination of the femoral canal in the range of 30° to 50° was in 63 % of the examined. In 37 %, the angle of inclination of the femoral canal was outside the optimal range. Table 1 shows the angles and percentages among 105 MRI examinations.

Point of entry of the femoral canal in the sagittal projection

In anatomic single-bundle reconstruction of the ACL, the point of entry of the femoral canal should be located at the attachment site of the native ACL. To determine the correctness of its location, the Bernhard and Hertel method is most often used, in which a rectangle with a grid is applied to an X-ray or computed tomography image. The main line that forms it is the Blumensaat line, tangent to the roof of the intercondylar fossa. Next, a parallel tangent to the lower edge of the lateral condyle is formed to this line. After that, a perpendicular is drawn to the previous two lines along the posterior edge of the lateral condyle and a perpendicular along its anterior edge. The resulting rectangle is evaluated in two directions — posterior-anterior and superior-inferior and divided evenly with a 5 × 10 mm grid. The optimal location in the posterior-anterior direction is considered to be 27 %, in the superior-inferior direction — 34 % [24, 25].

In our study, we adapted the Bernhard and Hertel method for MRI images and measured distances in mm and calculated in percentages by adding a standard proportion. Coronal, sagittal, and axial views were compared to visualize the entry point.

In anatomic single-bundle reconstruction of the ACL, the graft must provide anteroposterior and rotational stability. Therefore, the location of the femoral canal entry point is extremely important, as deviation from the anatomical one can lead to instability in a certain range of motion, limitation of movement, and graft damage. The optimal location was previously considered to be 24 % in the posteroanterior direction and 28 in the superior-inferior direction [24]. However, in recent anatomical studies, the average value is considered to be 27 % for the posteroanterior direction and 34% for the superior-inferior direction [24, 25]. In observation, taking into account the error, the optimal range is 20–30 % for the posteroanterior direction and 28–38 % for the superior-inferior direction.

In 42 cases, at least one indicator was equal to 0, that is, it went outside the rectangle and is 44 % of the total. In 25 % of patients in the posterior-anterior direction, the location of the canal was within 20–30 %, in the superior-inferior direction in 34 % of patients at the level of 28–38 %. However, only in 44 cases did the location of the canal in both directions correspond to the optimal limits, which is 46 % (Table 2).

Table 1

Femoral canal inclination angle on coronal projection

Inclination angle (reference values) (°)	≤ 17	17–32	32–39	39–50	≥ 50
Number of observations (%)	3	30	21	30	16

The location of the femoral canal entry point is a critically important step for the successful reconstruction of the ACL, since a significant error can lead to a negative result.

Position of the tibial tunnel on the sagittal projection

The location of the tibial tunnel on the sagittal projection should be localized along the Blumensaat line. The most commonly used method for measuring its position is the Amis and Jacob line, which passes through the widest part of the posterior angle of the medial tibial plateau, parallel to the medial joint line [24]. The center of the tunnel should ideally be located 43 % of the total sagittal distance of the tibial plateau, measured from the anterior edge of the tibial plateau. MRI measurements of the native ACL range from 27 to 60 % in some studies [24, 26] and from 28 to 63 % in others [27].

To measure the location of the tibial canal entry point, the projection on which the canal is best visible is selected and the Amis and Jacob line is drawn. First, the distance from the anterior edge of the tibia to the anterior edge of the tunnel is determined. Then, the same steps are performed for the middle of the tunnel and its posterior edge. The data are estimated in percentages by adding proportions.

Among all patients, the tibial canal was located at the anterior point less than 28 % in 21 % of cases. This indicator may indicate that in these individuals the tibial canal is located behind the Blumensaat line. It leads to impingement with the roof of the intercondylar fossa and the development of “cyclops syndrome”. In 19 patients out of 20, the ACL graft was destroyed, and in 1 case, signs of “cyclops syndrome” and graft damage were observed.

In 39 people, the canal was located at its posterior point by more than 63%, if it is located too posteriorly to the plateau, it can lead to rotational instability of the knee joint (Table 3).

Measurement of the distance of the tibial canal entry point

In Fig. 6, the canal is located at the anterior point by 59% and at the posterior point by 73%. The indicators indicate a too posterior location of the canal and a vertical graft.

Measurement of the inclination of the tibial canal in the coronal projection

The angle of inclination of the tibial canal is fundamental for the transtibial technique of anterior

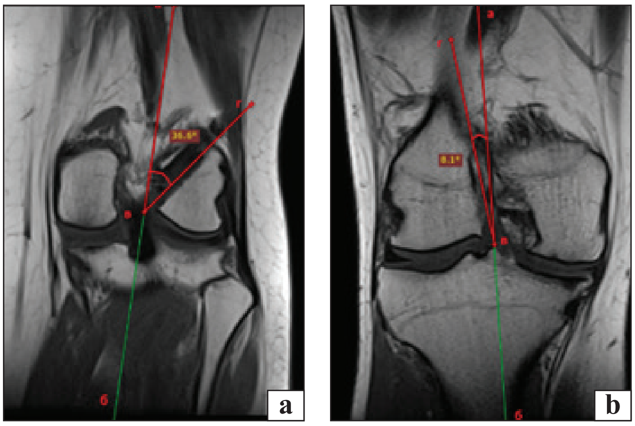

Fig. 1. Measurement of the angle of inclination of the femoral canal on the coronal projection: a) the angle is optimal and equal to 36.6°; b) the angle is too vertical and equal to 8.1° Line a–b is drawn through the middle of the diaphysis of the femur; line c–d is drawn through the femoral canal; abd is the angle of inclination of the canal

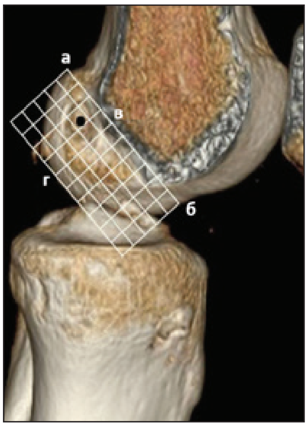

Fig. 2. Bernhard and Hertel method, 5 x 10 mm grid on the CT image to determine the point of entry of the femoral canal. Distance a–b is the posterior-anterior direction; c–d is the upper-lower; the black mark is the point of entry of the femoral canal, which is approximately 30% in the posterior-anterior direction and 27 in the upper-lower

cruciate ligament plastic surgery and should be within 65°–70° [28]. For the anatomical technique of PSL plastic surgery, it is not so fundamental, because the passage of the femoral canal does not depend on it. However, if the angle of inclination is too small due to the anatomical features of the tibial plateau, the length of the canal may be too short.

Insufficient canal length can make graft fixation difficult, especially with interference screws, and can also result in incorrect placement of the canal entry point. The sharper the angle, the more oval the exit point will be, rather than round, as the angle of inclination is directly related to the shape of the tibial canal exit [29]. Table 4 shows the relationship between the diameter of the canal entry point and the angle of inclination.

If the tibial canal exit point is oval, this can lead to widening of the canal and insufficient graft fit, which will complicate graft integration. Studies have shown that the most correct angle of inclination of the canal is ≥ 65° [30–34].

The angle of inclination of the tibial canal was measured as follows: the projection was chosen, where the beginning of the canal in the knee joint and its length were best visualized, a line was drawn parallel to the tibial plateau, a line was formed along the tibial canal to the plateau line, and the angle between these two lines was measured. If the distance was insufficient for accurate measurement of the angle, the line along the canal was projected. Of the 105 MRI studies, in 61 % of cases the angle of inclination was ≥ 65° (accepted as optimal), in 39 — < 65°.

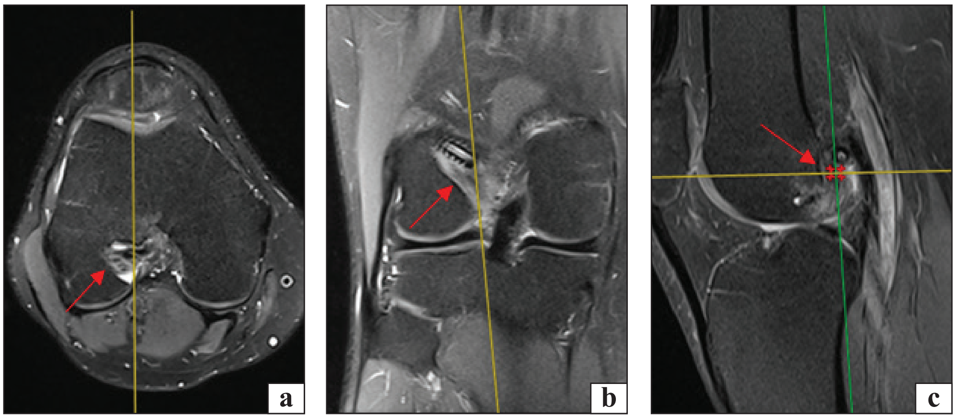

Fig. 3. Comparison of projections to determine the point of entry of the femoral canal. a — axial: the arrow indicates where the femoral canal is visualized in the extreme slice, the projection line of the sagittal slice; b — coronary: the arrow indicates the visualization of the femoral canal in the extreme slice, the projection line of the sagittal slice; c — sagittal, the arrow indicates the circle, the point of entry of the femoral canal, which is located at the intersection of the lines of the coronal and axial projections

Table 2

Femoral canal entry point measurement data using the Bernhard and Hertel method adapted for MRI

Direction	Posterior-anterior				Superior-inferior			
Reference values (%)	0	< 20	20–30	> 30	0	< 28	28–38	> 38
Number of observations (%)	11	4	25	60	34	19	34	13

Results

In 63 % of cases the angle of inclination of the femoral canal on the coronal projection was in the acceptable range of 30°–50°, and the most optimal values (32°–39°) were observed in 21 %. In 3 % of cases, the angle was less than critical (less than 17°), while in 16 % it exceeded 50°. The femoral canal entry point corresponded to the optimal limits in 46 % of examinations, while in 42 cases it went beyond the rectangle on the sagittal projection.

Regarding the tibial canal, its position on the sagittal projection corresponded to the anatomical limits in 38 % of cases, in 21 it was shifted anteriorly, and in 41 — posteriorly. In the posterior location, the graft was preserved in 24 % of examinations, and

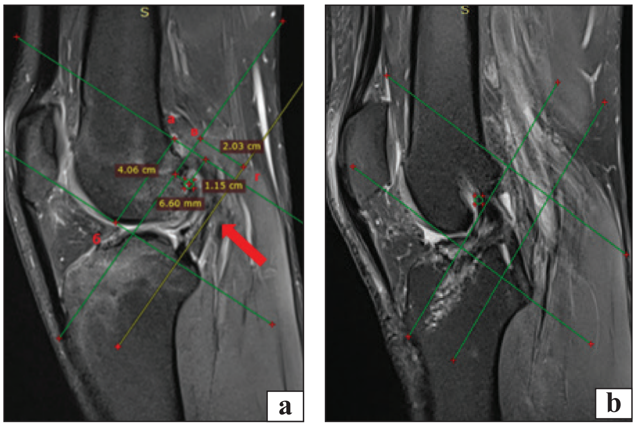

Fig. 4. MRI, sagittal projection. Line a–b is the posterior-anterior direction, line c–d is the superior-inferior. The arrow indicates the circle, the point of entry of the femoral canal. In the image, the point of entry is located in the posterior-anterior direction and 33% in the superior-inferior direction (a); the point of entry of the femoral canal is outside the Bernhard and Hertel rectangle (b)

Table 3

Data when measuring the tibial canal entry point on the sagittal projection

Reference values (%)	< 28	28–63	> 63
Number of observations (%)	21	38	41

Table 4

Dependence of the diameter of the channel entry point (mm) on the angle of inclination [29]

Tibial canal inclination angle	Canal diameter (mm)		
	8	9	10
35°	13,9	15,7	17,4
45°	11,3	12,7	14,1
55°	9,8	10,9	12,2
65°	8,8	9,9	11,0
75°	8,3	9,3	10,3

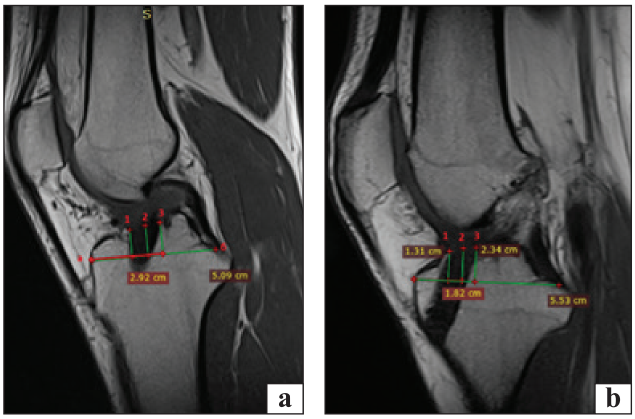

Fig. 5. Measurement of the point of entry of the tibial canal on the sagittal projection of MRI visualization. a–b is the Amis and Jacob line. 1 — the point of the anterior edge of the tibial canal, 2 — the point of the middle of the tibial canal, 3 — the point of the posterior edge of the tibial canal. In the image, the location of the canal is within: 33–57%, the middle is 46 % of the entire anterior-posterior distance of the plateau, and is within acceptable limits (a); 24–42 %, midpoint 33 % of the entire anterior-posterior distance of the plateau, and is too anterior. The graft is absent (b)

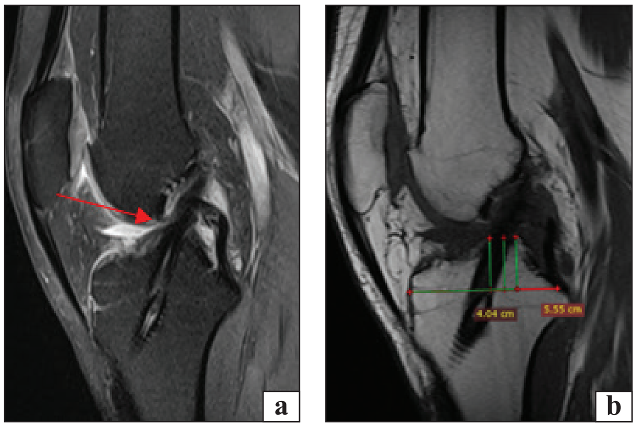

Fig. 6. Measurement of the tibial canal entry point on the sagittal projection of MRI imaging (a). Sagittal projection in T2 mode, the arrow indicates the integrated ACL graft (b)

in the anterior location — only in 6 %. The angle of inclination of the tibial canal on the coronal projection was within the normal range in 61 % of studies.

The obtained results indicate widespread technical deviations during the formation of channels for ACL reconstruction, which may affect the success of graft integration.

Discussion

The results of our study confirm the important role of accurate shaping of the femoral and tibial canals during ACL plastic surgery. In particular, deviations in the angles of inclination and the location of the entry points were found to directly affect the stability of the graft and the success of integration.

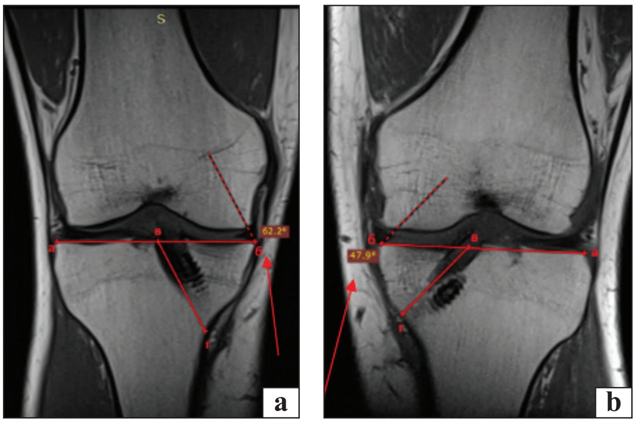

Fig. 7. Measurement of the tibial canal angle on the coronal projection. Line a–b is drawn parallel to the plateau, line c–d is drawn through the tibial canal. bcd — the angle of inclination of the canal, the arrow indicates degrees. The angle of inclination is 62°. The angle of inclination of the canal is too acute — 48° (b)

Similar values to ours are given in the works of K. D. Illingworth et al. and A. P. Parkar et al., who note that the optimal angle is 35°–45°, which prevents excessive verticalization of the ligament and joint instability [22, 34, 35].

J. P. Rue et al. also confirm the negative impact of angles < 25° on clinical outcomes [33]. Thus, our data are consistent with the above and demonstrate a significant frequency of technical errors in canal shaping.

The femoral canal entry point was located within the optimal anatomical landmarks in only 46 % of cases. Similar results were obtained by S. K. Nema et al., who found that only 35 % of femoral canals were correctly positioned, which caused graft impingement in 34 % of patients [36].

Our study showed that the tibial canal entry point corresponded to the anatomical boundaries on the sagittal projection in only 38 % of cases. This is consistent with the data of M. Sharma et al., who found that incorrect location of this canal leads to graft impingement and knee instability [37].

Regarding the tibial canal angle, the optimal angle of inclination of ≥ 65° was recorded in only 61 % of examinations. S. M. Howell et al. and R. Simmons et al. recommend 65°–70°, as acute angles are associated with shorter canals, poorer graft fixation, and an increased risk of loss of flexion [30, 31].

E. Pena et al. showed that an excessively acute angle promotes an oval canal outlet, which reduces graft adhesion to the walls [32]. In our study, it was smaller than recommended in 49 % of cases, which is consistent with other sources as a possible cause of impaired integration.

The use of MRI to study the location of the canals is effective. However, as noted in the study by A. Hart et al., even with the use of 3D MRI, accurate reproduction of their anatomical position remains a challenge [38].

Our study has several limitations: first, the retrospective nature may affect the objectivity of the assessment; second, the lack of clinical correlation with functional outcomes affects the analysis of technical errors.

Conclusions

Incorrect determination of the femoral canal inclination was found in 37 % of cases. Only in one of 105 examinations did this indicator exceed the normal range under optimal other parameters and a destroyed graft. This does not allow us to state that only the inclination of the canal in the coronal projection is the cause of failure. However, it may indicate a general error in the formation of the canal, in particular regarding its length.

The point of entry of the femoral canal is critically important. According to the adapted Bernhard and Hertel method, it was within the normal range in only 46 % of cases; in 42 cases, it was outside the rectangle in the sagittal projection. This indicates a possible error in determining the anatomical attachment site of the PSR, which can lead to instability, impingement, impaired integration and graft loss. The method requires further improvement, in particular, the development of software for MRI processing.

When measuring the angle of inclination of the tibial canal, it often turned out to be too sharp. Its influence is difficult to assess in isolation due to other technical errors. However, a dependence of the angle on the entry point was found, which may affect the integration of the graft.

In most cases, the canal was placed more posteriorly, which is probably related to the avoidance of impingement. In such cases, the graft was preserved 4 times more often than in the anterior location, which indicates the risk of impingement. At the same time, a too vertical location may not provide rotational stability.

The most anatomical placement of the canals is critical for successful reconstruction. The most important technical factors remain the determination of the entry points of the femoral and tibial canals. The angle of inclination is less fundamental, but may indicate technical errors. Accordingly, thorough planning, precise identification of anatomical landmarks, and, when appropriate, the implementation of navigation or EOC are essential.

Conflict of interest. The authors declare that there is no conflict of interest.

Prospects for further research. Despite the limitations, the results of our study highlight the importance of accurately determining the entry point and angle of the canals during ACL reconstruction. The use of MRI as a tool for preoperative planning and postoperative analysis may help surgeons avoid technical errors and improve treatment outcomes.

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Authors' contributions. Kostrub O. O. — idea and concept of the study, assessment of findings, drawing conclusions; Didukh P. V. — structuring and drafting the article, choosing research methods; Nikiforova I. M. — preparation and selection of MRI studies; Zasadnyuk I. A. — data summary of the study results, statistical analysis of the results; Blonsky R. I. — evaluation and discussion of the results; Podik V. A. — literature search, compiling the reference list, data summary in Excel spreadsheet.

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CRITICAL PARAMETERS OF TUNNEL POSITIONING IN ACL RECONSTRUCTION: A RETROSPECTIVE MRI ANALYSIS

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