BMC Musculoskeletal Disorders

RESEARCH Open Access

The significance of guiding anterior cruciate ligament revision: a modified femoral tunnel classification

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Abstract

Background The positioning error of femoral tunnel was the key factor leading to the failure of anterior cruciate ligament (ACL) reconstruction. This study aimed to propose a new femoral tunnel classification to guide revision ACL reconstruction.

Methods Totals of 150 patients with ACL reconstruction failure from 2017 to 2023 were enrolled in this retrospective study. According to the tunnel diameter, shape, posterior wall and the positioning relationship with the Lateral Intercondylar Ridge on the three-dimensional CT imaging, we divided the femoral tunnels into four types: Type I off-target type, Type II straddled type, Type III anatomical type, and Type IV irregular type. Finally, explored the inter-observer reliability within two groups of doctors (Group A, 12 high seniorities; Group B, 12 low seniorities), and evaluated the intra-observer reliability within 6 doctors after two months. Clinical evaluation was performed using the Lysholm score, Tenger activity score, Pivot Shift and anterior knee laxity measurements.

Results Among 150 cases of femoral tunnel three-dimensional CT reconstructed imaging, 144 cases were successfully included in the classification system, and 6 cases were confirmed as uncertain type. We measured the Kappa (κ) coefficient of group A was significantly higher than that of group B (κ 0.72 VS 0.68), and the κ coefficient of group A was still higher than group B (κ 0.69 VS 0.62) after further dividing Type III anatomical type into three subtypes. In addition, the κ coefficients of intra-observer reliability were all exceeded 0.73. Clinical follow-up showed that 9 patients had good knee joint motor function and stability after operation.

Conclusion The new femoral tunnel classification was reliable and had clinical guiding significance based on three-dimensional CT imaging.

Level of evidence Level III.

Keywords Anterior cruciate ligament, Revision, Femoral tunnel, CT, Classification

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Background

Recently, the number of patients with knee anterior cruciate ligament (ACL) injuries has gradually increased due to the rapid development of competitive sports and the widespread development of mass sports [1]. Arthroscopic ACL reconstruction was usually needed to restore the motor function of knee after severe ACL injury. However, the sharp increase in the number of ACL reconstructions was accompanied by numerous failure cases [2]. The failure rate of 5 years after ACL reconstruction was as high as 5-25% [3, 4]. Previous studies have confirmed the tunnel, graft types, Single or double-bundle reconstruction and other many factors would lead to the failure of the ACL reconstruction, but the wrong position of femoral tunnel was considered as the key factor [5, 6].

After the failure of the initial ACL reconstruction, it was difficult to identify and determine the appropriate location of femoral tunnel during the revision process [7–9]. If the tunnel position was improper, it was necessary to choose another tunnel or fill the initial tunnel for a second-stage operation [10]. In addition, in order to enhance the rotational stability of the knee and improve the success rate of the revision ACL reconstruction, some scholars have proposed a combined extra-articular reconstruction on the basis of primary revision ACL reconstruction, and achieved satisfactory clinical results. However, compared with isolated ACL reconstruction, performing the procedures such as LET or ALL will increase the technically difficult and the medical expenses of patients [11, 12]. The clinical evaluation of the location of femoral tunnel is mainly performed by X-ray or computed tomography (CT) [13], but it cannot obtain the specific position of the femoral tunnel. Although Magnussen et al. had proposed the femoral tunnel classification system for the revision ACL reconstruction [14], it had not been widely applied in clinical practice. The method is considered too simplistic to adequately address the complexity of the revision ACL reconstruction cases and to formulate an effective revision plan.

There were few studies on the classification of femoral tunnel of the revision ACL reconstruction, which may be related to when the tunnel is not well-positioned, a single stage revision is possible in almost every case using the outside-in technique [15]. This study aims to propose a new femoral tunnel classification based on three-dimensional CT imaging, which combined with the femoral tunnel diameter, shape, posterior wall and the positioning relationship with the Lateral Intercondylar Ridge (LIR) [16]. The hypothesis was that the new classification would improve the accuracy of femoral tunnel positioning in the revision ACL reconstruction and could be applied in clinical practice to solve the complex femoral tunnel positioning problem in the revision ACL reconstruction and find the best tunnel creation method for each patient.

Methods

Data sources and search start

In total, 150 cases three-dimensional CT images before revision ACL reconstruction surgery were collected in this retrospective study from 2017 to 2023 in a multicenter hospital cooperative study, and the study was reviewed by the ethical review committee of The Hebei Medical University Third Hospital (No:2022-057-1). The study inclusion criteria were as follows: the affected knee had the history of ACL reconstruction. The following exclusion criteria were applied: combined posterior cruciate ligament, anterolateral complex or anteromedial complex injuries requiring surgery; severe Kellgren–Lawrence grade≥3) osteoarthritis; the patient had a history of femoral condylar fracture.

Three-dimensional CT reconstruction

All patients were scanned by CT (omatom Definition AS 128, Siemens, Germany) to obtain the image data of continuous scanning of knee joint, then imported them into CT three-dimensional reconstruction software (Mango, China). After removing muscle tissue, we could get a complete knee model Then, rotated the model into the standard anteroposterior position, and cut the highest point of the intercondyle fossa to obtain the pure sagittal image of the lateral condyle along the long axis direction of femur after removing the tibia and patella (Fig. 1). Next, we defined the location of the LIR [17], and drawn the anatomical femoral axis (FH) and the Blumensaat line (AC). Then, calculated the quarter-point B of the AC, and drawn the EG through the point B, with the angle between EG and FH being 137°. According to previous studies confirming that LIR intersected 25% of the Blumensaat line depth, the BG line just was the LIR [17]. Then, determined the center of the tunnel (point O) in the pure lateral view of the lateral femoral condyle, and measured the radius of the tunnel (r_1). Next, gradually increased the radius of the point O in the circle to the posterior edge of the lateral wall of the intercondylar fossa to determine the radius (r_2) of the circle tangent to the posterior femoral condyle, and $D = (r_2 - r_1)$ was measured (Fig. 2). Last, determined the maximum diameter of the tunnel in the continuous CT axis sequence.

Femoral tunnel classification

This femoral tunnel classification system comprehensively considers the shape of the Old Tunnel (OT), the LIR, the positional relationship between OT and LIR (intersection, tangency, and separation), the maximum diameter (d) of the OT, the minimum distance (D) of the posterior wall, and the relationship between OT

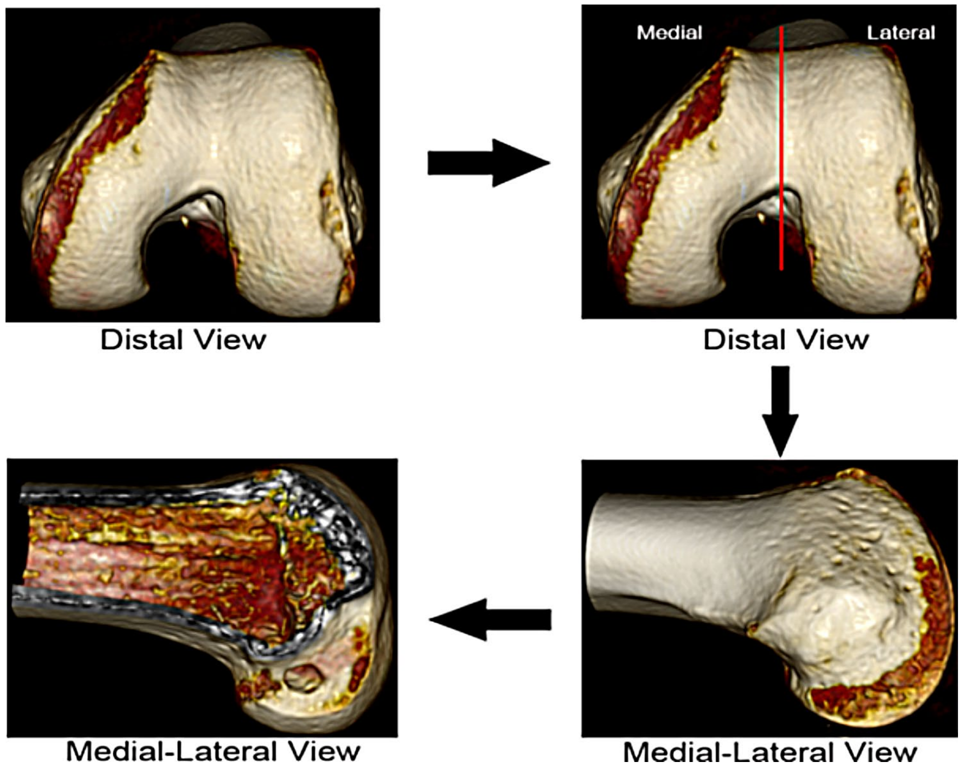

Fig. 1 Three-dimensional CT imaging of the femoral condyle and tunnel

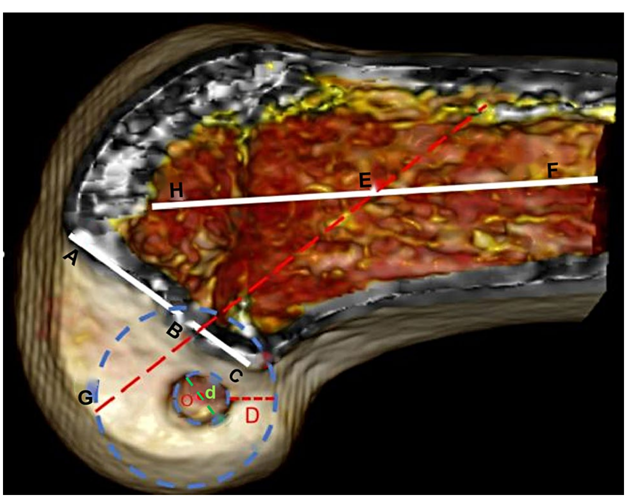

Fig. 2 Three-dimensional CT imaging of the lateral femoral condyle, Lateral Intercondylar Ridge and the minimum distance of the OT's posterior wall. FH: anatomical femoral axis; AC: Blumensaat line; BG: Lateral Intercondylar Ridge; d:the maximum diameter of the OT; D: the minimum distance of the posterior wall

and ACL femoral footprint (separation, intersection and inclusion). We divided the relationship between OT and surrounding bony landmarks into four types and three subtypes (Table 1; Fig. 3).

Reliability assessment

All three-dimensional CT imaging were numbered and annotated with the LIR, the minimum distance of the posterior wall, and the diameter of the OT were performed by one senior doctor. Then, under the condition that the images were not marked and disrupted, the femoral tunnels were classified by two groups of doctors with different seniorities (Group A, 12 high seniorities who alone performed more than 100 ACL reconstruction operations and more than 20 revision operations; Group B, 12 low seniorities who alone performed less than 50 ACL reconstruction operations and less than 10 revision operations) according to the classification method, and explored the inter-observer reliability within two groups of doctors, evaluated the intra-observer reliability within 6 doctors who were randomly selected from the Group A and B after two months.

Clinical evaluation

We conducted a retrospective analysis of patients who were admitted to the The Third Hospital of Hebei Medical University for the revision ACL reconstruction between 2022 and 2023. All patients agreed and signed an informed consent form for the procedure. The study inclusion criteria were as follows: Patients agreed and signed an informed consent form; the affected knee had the history of ACL reconstruction; patients with least grade II laxity (>6.0 mm) by the Anterior drawer test and

Table 1 Anterior cruciate ligament femoral tunnel classification

Type		**Figure**	**OT**		
			Position	**To LIR**	**To femoral footprint**
I		3a	extreme anterior	separation	contained by the femoral non-footprint
II		3b	mild to moderate anterior	intersected or tangent	the main area of the tunnel was not included in the femoral footprint
III	IIIa	3c	proper position	separation	the main area of the tunnel was within the femoral footprint, d ≤ 9.0 mm, D ≥ 1.5 mm
	IIIb	3d	proper position	separation	the main area of the tunnel was within the femoral footprint, d > 9.0 mm, D ≥ 1.5 mm
	IIIc	3e	proper position	separation	the main area of the tunnel was mainly within the femoral footprint, D < 1.5 mm
IV		3f	irregular tunnel	-	the tunnel was non-round/non-oval, such as multi-tunnel, rectangular and other shapes

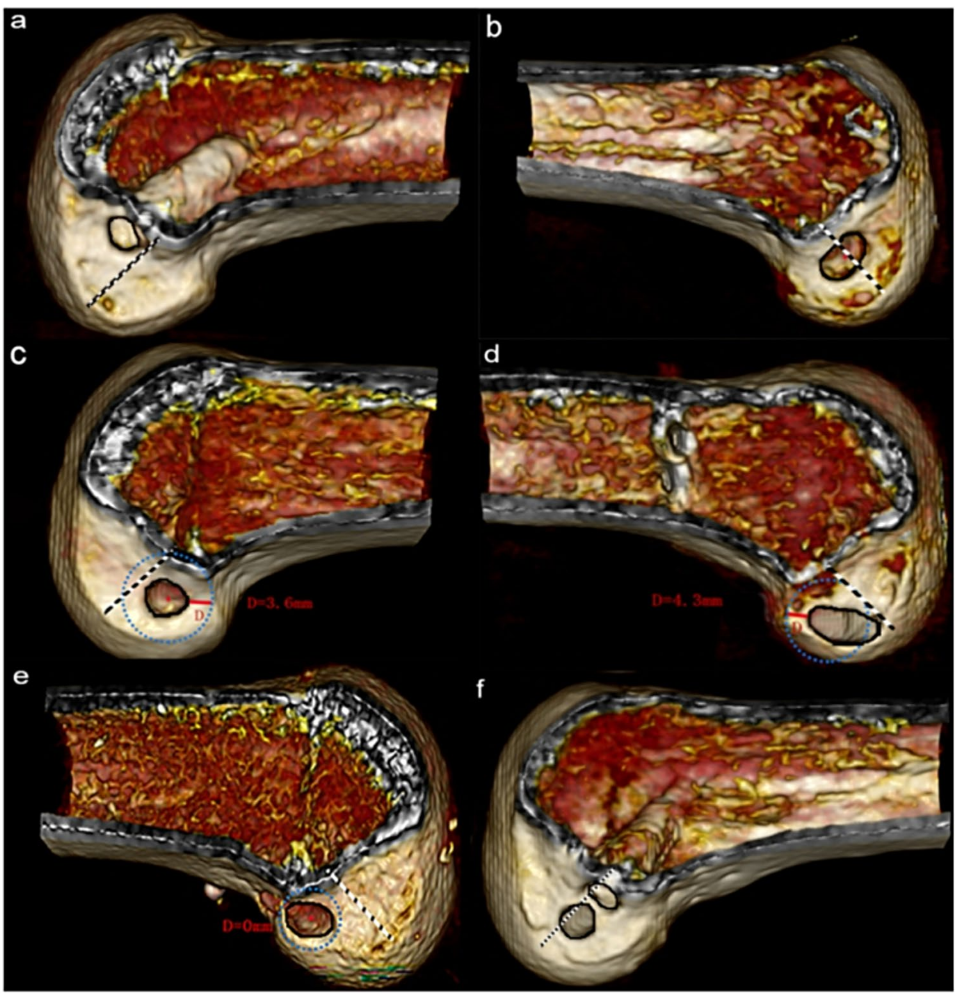

Fig. 3 Three-dimensional CT imaging of femoral tunnel classification system. **a**: Type I off-target type The tunnel was separated from the LIR and contained by the femoral non-footprint; **b**: Type II straddled type The tunnel was intersected or tangent with the LIR, and the main area of the tunnel was not included by the femoral footprint; **c**: Type IIIa anatomical in-suit type The center of the tunnel was separated from the LIR and the tunnel mainly within the femoral footprint, d ≤ 9.0 mm, D ≥ 1.5 mm; **d**: Type IIIb anatomical enlarged type The center of the tunnel was separated from the LIR and mainly within the femoral footprint, d > 9.0 mm, D ≥ 1.5 mm; **e**: Type IIIc anatomical posterior type The center of the tunnel was separated from the LIR and was mainly within the femoral footprint, D < 1.5 mm; **f**: Type IV irregular type. The tunnel was non-round/non-oval, such as multi-tunnel, rectangular tunnel, belt tunnel and other shapes

pain or a feeling of knee instability; preoperative MRI and X-ray imaging diagnosed ACL injury and intraoperative arthroscopic exploration clearly diagnosed ACL injury. The following exclusion criteria were applied: combined posterior cruciate ligament, anterolateral complex or anteromedial complex injuries requiring surgery; severe Kellgren–Lawrence grade ≥ 3) osteoarthritis; the patient had a history of femoral condylar fracture; and surgery

Table 2 Distribution of femoral tunnel types and three subtypes

Tunnel location	Number
Type I off-target type	14
Type II straddled type	40
Type III Anatomic type	71
IIIa anatomical in-suit type	22
IIIb anatomical enlarged type	32
IIIc anatomical posterior type	17
Type IV irregular type	19
Uncertain type	6
Uncertain type in the Type III	4

Table 3 The consistency of inter-observer reliability

	Kappa index number	
	Group A ($n=12$)	Group B ($n=12$)
Type I, II, III, IV	0.72	0.68
Type I, II, III (IIIa, IIIb, IIIc), IV	0.69	0.62

contraindicated owing to chronic illness. Using the above criteria, we enroled 9 patients (mean age 32.9±7.0 years; 7 male, 2 female), a mean follow-up of 12.6±2.5 months. Clinical evaluation of the outcome was conducted using the Lysholm score, Tenger activity score, the degree of Pivot Shift (ORTHOKEY, ITALIA) and an objective measurement of anterior knee laxity using the Ligs (Shanghai, China).

Statistical analysis

Statistical analysis was performed using SPSS 22.0 software. Count data were expressed as X, t-test was used for normally distributed continuous variables, Rank test was used for non-normal data, and $\rho<0.05$ was considered statistically significant. The Kappa coefficient (κ) was an indicator used to assess the intra and interobserver reliability of the subtype [18], and the κ values of 0.00–0.20 indicated slight agreement; 0.21–0.40 indicated fair agreement; 0.41–0.60 indicated moderate agreement; 0.61–0.80 indicated substantial agreement; 0.81–1.00 indicated almost perfect agreement [19]. Previous literature reported that the maximum revision rate of ACL reconstruction is 25%. In the sample size calculation, we assumed that the Confidence Level was 95%, the margin of error was 10%, and the Population Size was 3000 from 2017 to 2023 in Hebei Medical University Third Hospital. We can get that the minimum sample size of patients needed for the study was 71, and the sample size finally included in this study was 150 cases.

Results

Femoral tunnel classification

The femoral tunnel classification system was accepted and learned by all 24 doctors based on three-dimensional CT imaging. The uncertain type was defined by at least nine doctors hold different opinions on the classification of the same patient. Finally, there were 144 cases of 150 tunnels were correctly divided while only 6 cases were identified as uncertain type (Table 2).

The results of consistency analysis suggested that among the above four types, the score of group A was significantly higher than that of group B (κ 0.72 VS 0.68). After further dividing the anatomical type into three subtypes, the consistency score of group A was still higher than that of group B (κ 0.69 VS 0.62) (Table 3). In addition, the κ coefficients of intra-observer reliability within 6 doctors were all exceeded 0.73 (Table 4).

Clinical evaluation

According to the femoral tunnel classification system, We reconstructed the preoperative CT model of 9 patients with CT three-dimensional reconstruction, and found there were 3 patients belonged to Type II, 2 patients belonged to Type IIIa, 2 patients belonged to Type IIIb, 1 patient belonged to Type IIIc and 1 patient belonged to Type IV. At a follow-up mean of 12.6±2.5 months, clinical assessment of the revision ACL reconstruction knees showed a statistically significant difference between the preoperative and the latest follow-up clinical scores (Table 5). In addition, there was no obvious pain and and other adverse symptoms in 9 patients after operation.

Discussion

The main achievement of this study was that we proposed a new femoral tunnel classification system based on three-dimensional CT imaging to guide the revision ACL reconstruction surgery on the basis of comprehensive consideration of the femoral tunnel shape, position, diameter, and posterior wall of the OT, and it was proved that this classification system had high reliability and could be used in clinical practice.

The classification aimed to describe the position of the femoral tunnel with surrounding bony landmarks for the selection of different operation method for the revision ACL reconstruction. Zauleck et al. found LIR was a reliable bony landmark helping the surgeon analyze and judge the anterior and posterior location of the tunnel [20]. However, it was difficult to identify the specific

Table 4 The κ consistency of intra-observer reliability

	κ consistency					
	Doctor 1	Doctor 2	Doctor 3	Doctor 4	Doctor 5	Doctor 6
Type I, II, III, IV	0.75	0.81	0.74	0.72	0.79	0.83
Type I, II, III (IIIa, IIIb, IIIc), IV	0.79	0.76	0.71	0.70	0.74	0.76

Table 5 Comparison of preoperative and the latest follow-up clinical scores

	Lysholm score	Tenger activity score	The degree of Pivot Shift	Anterior knee laxity(mm)
Preoperative	60.9 ± 4.6	3.8 ± 0.8	2.1 ± 0.7	5.2 ± 1.1
Postoperative	82.6 ± 3.6	7.8 ± 0.9	0.6 ± 0.5	1.6 ± 0.7
P	0.00	0.00	0.00	0.00

location of LIR on CT two-dimensional imaging due to the influence of the OT [21, 22], and the LIR was almost entirely dependent on relative anatomical knowledge and clinical experience in the Magnussen femoral tunnel classification, which substantially decreased the objectivity of the results [14]. Therefore, in this study, we successfully located the precise position of LIR in the femoral model through the three-dimensional CT reconstruction technology and the anatomical characteristics of LIR, and proposed our femoral tunnel classification system according to the position between the LIR and OT (intersection, tangency, and separation). Moreover, although the consistency of the four types in the high senior group was higher than that in the low senior group, the low senior group had also high reliability while the consistency of intra-observer reliability all exceeded 0.73, so we believe the new classification system can help the low senior doctor increase the recognition of femoral tunnel classification.

Due to the shortage of clinical experience, the Type I off-target type tunnel was often misplaced in an extreme anterior position by lower seniority doctors, but we found this type had a minimal impact on the revision ACL reconstruction, because we could directly placed the New Tunnel (NT) in the ACL femoral footprint to complete the single-stage revision (Fig. 4a). In addition, this study did not further divide Type II straddled type into forward, vertical, and forward vertical subtypes like the Magnussen type II (Fig. 4b) [14], because the research results of Magnussen et al. have shown that this classification was easily confused in the narrow ACL femoral footprint, and the three subtypes have little influence on the choice of revision strategies. Regardless of the subtype of OT, directly placing the NT in the narrow ACL femoral footprint would intersect with OT to form a huge tunnel, and expanding the OT will make NT more anterior, which would make OT unable to be used in single-stage revision. Therefore, the Type II straddled type corresponding to Magnussen type II in this study was not further divided into subtypes, due to the tunnel expansion was an important factor contributing to the failure of the revision ACL reconstruction and the enlarged tunnel frequently led to tunnel burst [20, 23].

In order to make the choice of revision strategy more instructive, the Type III anatomical type was further divided into three subtypes combined with OT diameter and posterior wall: IIIa in-suit type, IIIb enlarged type

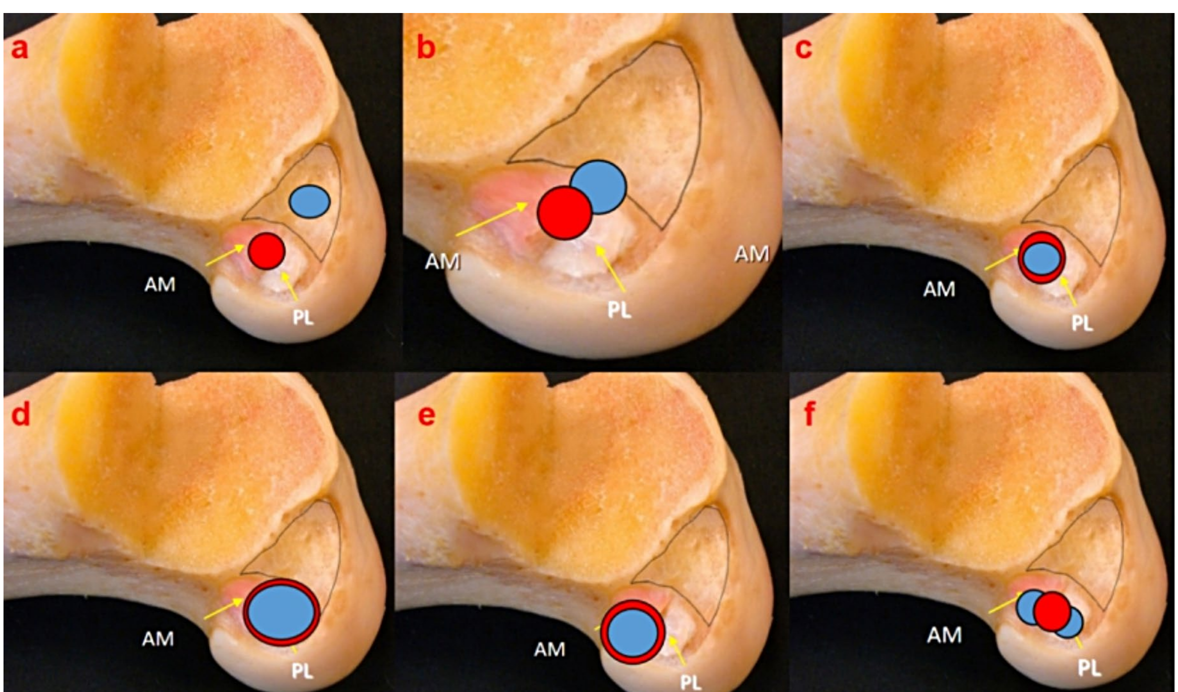

Fig. 4 Schematic diagram of corresponding treatment choices for different femoral tunnel classification. **a**: Type I off-target type; **b**: Type II straddled type; **c**: Type IIIa anatomical in-suit type; **d**: Type IIIb anatomical enlarged type; **e**: Type IIIc anatomical posterior type; **f**: Type IV irregular type. Blue circle: old tunnel; Red circle: new tunnel; AM: anteromedial; PL: posterolateral

and IIIc posterior type. Firstly, the OT could be directly expanded by at least >1.0 mm to complete the single-stage revision as NT in the IIIa in-suit type (Fig. 4c). Secondly, If the OT is in a proper position with bone tunnel enlargement, a wide array of different tunnel properties including altered size, shape, and trajectory. For mild bone tunnel enlargement, it is considered to have only mild widening and be amenable to routine revision, but primary bone grafting and staged reconstruction should be considered when the bone tunnel is obviously enlarged in IIIb enlarged type (Fig. 4d) [24, 25]. Finally, in the IIIc posterior type, we should also focus on the femoral graft fixation method to avoid the fixation failure caused by the tunnel burst after extrusion fixation, which requires detailed preoperative planning (Fig. 4e). It's noteworthy that the division of these subtypes was based on the diameter and posterior wall of the OT rather than the position. Although the position of OT in the anatomical region would have differences in the in-situ tension and mechanical properties of the graft, the difference would not directly determine the success or failure of the revision process just as the diameter and posterior wall of femoral tunnel in complex revision cases, and whether the tunnel should be located in high or low position in ACL anatomical regions were difficult to reach a consensus [26]. Nevertheless, the single-stage revision should be considered for enlarging the tunnel regardless of high or low position in the lateral wall of the intercondylar fossa in the Type IIIa in-suit type.

In addition, this study set the cutoff values at D=1.5 mm and d=9.0 mm to distinguish the three subtypes of Type III anatomical type. On the one hand, recent research has shown that a sufficiently wide posterior wall of femoral tunnel was helpful to improve the success rate of ACL reconstruction. Also, there is a risk of tunnel bursting when D <1.0 mm, and the tension of the graft will increase and the graft survival will reduce when D >2.0 mm. Therefore, we take the average distance (D=1.5 mm) as the cutoff value of the posterior wall of femoral tunnel in the Type III anatomical type. On the other hand, previous literatures have showed that the graft with a diameter of 7.0–10.0 mm can make the graft have enough strength in the middle and late stage of activation, which makes the knee joint have better stability and reduces the incidence of reoperation after operation [27, 28]. In addition, when choosing to directly expand the old tunnel to build a new tunnel during the process of ACL revision, it is necessary to expand the old tunnel by at least 1.0 mm to achieve structured repair of tendon-bone interface, so we choose D=9.0 mm as the cutoff value of the diameter of femoral tunnel.

According to the tunnel shapes in clinical practice, we further proposed the Type IV irregular type based on improving the accuracy of the Magnussen femoral tunnel classification, which could more systematically cover clinical surgery. For example, the femoral double tunnel was difficult to make a selection of revision strategy, and even if the position of the double tunnel was correct, the expanded double tunnel could still probably run through a huge tunnel (Fig. 4f) [29]. Therefore, we can choose a second-stage revision or "Over-The-Top" reconstruction could be chosen to deal the difficult problem. However, according to the location and shape of the bony tunnel, it is feasible to perform a single-stage revision even after a double bundle procedure.

There are some limitations in this study. Firstly, only 150 cases CT imaging were included in the retrospective study, but the patients included were from multi-center hospitals, all of whom need revision ACL reconstruction and the location of femoral tunnels were complex. Secondly, some recent studies have reported that changing the direction of tibial tunnel could also improve the success rate of revision ACL reconstruction [30]. However, this study only focused on the classification of femoral tunnel at present, so we need to supplement the study of the tibial tunnel in the follow-up study. Finally, the LIR was determined by the positional relationship of the anatomical femoral axis and the Blumensaat line, so it may differ from the actual situation due to individual differences. However, we believe the classification system combined with the exact anatomical parameters would be more objective than the Magnussen femoral tunnel classification.

Conclusions

Based on the three-dimensional CT imaging and the femoral tunnel, the new ACL femoral classification is potentially reliable, repeatable, and has high clinical guiding value. However, the modified femoral classification system still needs long-term clinical follow-up to explore its clinical application value.

Abbreviations

ACL	Anterior cruciate ligament
CT	Computed tomography
ICC	Interclass Correlation Coefficient
MRI	Nuclear magneticresonance
κ	Kappa
LIR	Lateral Intercondylar Ridge
OT	Old Tunnel
D	The minimum distance of the posterior wall
d	The maximum diameter of the old tunnel
NT	New Tunnel

Acknowledgements

The authors are grateful to the Hebei Medical University Third Hospital and other hospitals for providing the CT imaging data.

Author contributions

Y.Z.N. and Z.C used CT to reconstruct the tunnel, analyzed data and wrote the paper. L.P.J. and Z.K.L. collected the data and helped to write the paper. Y.Z. and Z.D.Z. and Y.S.L. searched for literature, helped to collect the data and guide the development of research.J.T.D. conceived the study, revised the manuscript.

Funding

This study was supported by the "14th Five-Year" clinical medicine Innovation Research Team Support program of Hebei Medical University(2022LCTD-B25), and Science and Technology Department of Hebei Province assisted Xinjiang science and technology plan project (V164483028949); the National Natural Science Foundation of China (No. 82172460).

Data availability

The data analyzed in this study were taken from clinical research combined with imaging research, which can be found from Pubmed. The original data can be contacted with the correspondent: Jiangtao Dong, Email: djtloveyz@outlook.com, Tel: 0311-88602801.

Declarations

Ethical approval

This retrospective study was approved by the ethical review committee of The Hebei Medical University Third Hospital (ethics no: 2022-057-1).

Informed consent

Not applicable.

Competing interests

The authors declare no competing interests.

Received: 10 March 2024 / Accepted: 10 September 2024
Published online: 16 September 2024

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