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SCFE Screw Trajectory Designing Method Integrating Greedy Algorithm and Genetic Algorithm Based on 3D CT Images

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Abstract. This study proposes an innovative method for designing screw trajectories in treating slipped capital femoral epiphysis (SCFE) using 3D CT imaging and a hybrid of greedy and genetic algorithms. Bone features from 78 pediatric SCFE patients were segmented, and a preliminary screw trajectory was designed using a greedy algorithm. An evaluation index, guided by Beijing Jishuitan Hospital specialists, was established and optimized with genetic algorithms. The results align with current literature and show promise in enhancing surgical efficiency, marking a significant advancement in SCFE treatment.

Keywords. SCFE screw trajectory, image segmentation, greedy algorithm, genetic algorithm

1. Introduction

Slipped capital femoral epiphysis (SCFE) is a prevalent hip disorder among adolescents[1], characterized by the femoral head's structural composition and the weakness of the growth plate in the femur's upper part. The condition is marked by the femoral epiphysis moving downwards and backwards relative to the symphysis, staying within the acetabulum. SCFE's incidence rate is up to 1.8 per 10,000 adolescents, typically affecting those between 8-15 years old[2]. Neglecting timely treatment can lead to severe complications, compromising hip function. Surgical intervention involves securing the femoral epiphysis in situ using screw fixation, guided by a hollow nail under X-ray fluoroscopic guidance. The classification of symptoms into mild, moderate, and

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severe is based on the slip angle and femoral neck width, necessitating preoperative design of screw trajectory parameters tailored to the specific symptoms for successful surgery and optimized patient outcomes.

In current SCFE surgery, screw trajectory determination is largely based on the surgeon's experience, with intraoperative imaging relying on adjusting the X-ray for 90° angles and continuous fluoroscopy to identify the best bone profile for screw placement. This method is complicated by femoral deformity, changes in limb position post-anesthesia, and interference from the operating bed, leading to planning inaccuracies on non-standard images and potential surgical complications. Additionally, repeated fluoroscopy increases radiation exposure. To address these issues, this study advocates for preoperative surgical planning using 3D CT images to design the screw trajectory, requiring precise extraction of bone features and identification of the optimal trajectory on a segmented bone model. This shift to preoperative planning could greatly improve surgical precision, reduce radiation exposure, and enhance procedural efficiency.

nnU-Net[3] is a leading deep learning-based segmentation method in biomedical imaging, proven effective in segmenting diverse anatomical structures such as craniomaxillofacial[4], aortic[5], and fetal brain tissues[6]. Its accuracy and adaptability make nnU-Net suitable for this study's requirements, ensuring precise bone feature segmentation crucial for preoperative planning in SCFE surgery. Selecting the optimal screw trajectory is an optimization problem well-suited to genetic algorithms[7], which offer rapid and probabilistic global search capabilities. These algorithms have been successfully applied across various domains, and are known for their versatility and effectiveness. In biology, genetic algorithms have been applied by Hesami et al. to optimize the growth medium for chrysanthemum branching[8] and by Sirohi's team to model and enhance cellulose production in Aspergillus rhamnosus[9]. In robotics, Hao and co-authors utilized an improved genetic algorithm for mobile robot path planning[10], while Abdelatti and associates used a design of experiments approach to optimize genetic algorithms for vehicle path optimization[11]. This study plans to use a hybrid approach, combining genetic algorithms with greedy algorithmic principles, to optimize screw trajectory selection in SCFE surgery. This method aims to enhance preoperative planning, ensuring efficient and effective surgical strategies for SCFE treatment.

2. Materials and methods

2.1. Sources of data and Bone feature segmentation

To enhance the algorithm's real-world applicability, this study employed actual patient data from Beijing Jishuitan Hospital of Capital Medical University. CT images from 78 pediatric patients with epiphyseal slips, aged 6.11 to 14.08 years (mean age 10.85), were included. The patient cohort comprised 63 males, 15 females, with 26 left-sided, 28 right-sided, and 24 bilateral slips. Raw DICOM format data with 1 mm CT slice thickness was used, ensuring the clinical relevance and fidelity of the dataset for algorithm development and testing.

For efficient annotation and processing, ITK-SNAP[12] software converted CT DICOM images to NIFTI format. The median sagittal section (MSS) identified the affected side for each patient, with bilateral slips divided into two cases and unilateral slips as individual cases. This method produced 102 cases—50 left-side and 52 right-side CT images—balancing the dataset for analysis.

The SCFE surgery screw trajectory starts on the femur surface, traverses the femur, and ends near the subchondral bone, 2-3 mm away. This study focused on extracting the relevant bone features from CT images: the femur, its epiphyseal edge, the femoral head, and subchondral bone. With an orthopaedic surgeon's guidance, CT images were annotated, and the nnU-Net neural network was trained to extract these features, resulting in 3D models for trajectory planning and analysis.

2.2. Design of screw trajectories

This study introduces a novel method for SCFE surgery planning by recognizing the critical relationship between segmented bone structures and the screw trajectory. It involves using the greedy algorithm to generate an optimal trajectory for each bone structure individually, based on their shape and position. The study then defines a prismatic optimal region, asserting that the ideal trajectory must fall within this zone. This approach ensures anatomical precision and considers the unique geometry of each structure, improving the customization and accuracy of surgical plans.

To objectively evaluate the designed screw trajectory parameters, this study, guided by an orthopaedic surgeon, created an evaluation index for SCFE surgery. The index measures the variability of the optimal trajectory using the length of the bone feature through which the screw passes. By concentrating on a specific bone structure in the pre-design phase, the study intends to offer a more objective and persuasive assessment of the screw trajectory parameters. This systematic evaluation ensures the design's relevance to surgical practice and provides a practical standard for the proposed algorithmic method's effectiveness.

A genetic algorithm is used to customize optimal screw trajectory parameters for individual patients within the optimal region. The screw trajectory evaluation index acts as the fitness function for the algorithm. Through iterative searches, the algorithm refines solutions to pinpoint the best trajectory design within the specified range. This process ensures that the chosen trajectory is both anatomically correct and optimized for each patient's unique traits, improving the surgical plan's precision and effectiveness.

3. Results

3.1. Bone feature segmentation results

Using nnU-Net, we have successfully extracted various critical bone features related to epiphyseal slip surgery from CT scans, as illustrated in **Figure 1**. The left side shows a CT scan with its transverse, sagittal, and coronal planes, while the right side displays the network's segmentation of these data. The segmented features include the femoral head contour, femur, subchondral bone, and the femoral head epiphyseal edge. The extracted features achieved learning accuracies of 93.44%, 96.27%, 89.76%, and 89.73% using annotated data. nnU-Net was also employed for automatic 3D reconstruction of these features, resulting in a detailed bone model as shown in **Figure 2**(a,b,c,d for different perspectives). This model accurately describes the patient's skeletal structures and provides robust data for pre-designing screw trajectory range parameters in surgical procedures.

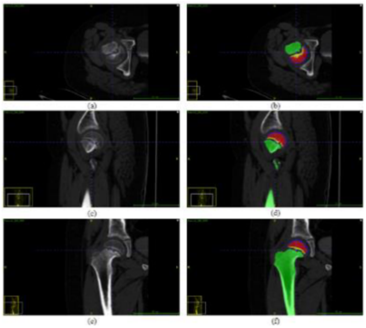

Figure 1. Network segmentation results in different directions

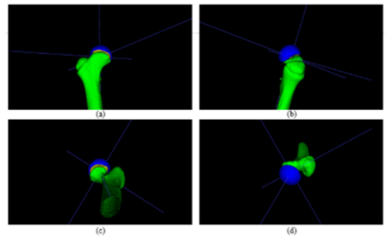

Figure 2. 3D display of network segmentation results

3.2. Results of the pre-design of the screw trajectory

(1) Design of screw trajectory generation methods

This study provides the process of generating screw trajectories, which is tailored to specific bone structures based on surgeon expertise. The study conducted curve fitting on various bone structures and identified characteristic lines from the graphs. This line is represented as L . Since the screw trajectory is a line segment in three-dimensional space, the path for screw placement is determined along this line. This method optimizes the trajectory for the bone structure's unique geometry, enhancing the precision and efficiency of the surgical procedure.

In determining the start and end points of the screw trajectory, our study relies on clinical advice and surgical practicalities. The proposed start point is at the femoral head boundary, and the end point is 2-3 mm within the femoral head from the subchondral bone. **Algorithm 1** has been designed to identify the appropriate start point $P_1(x_1, y_1, z_1)$ and the end point $P_2(x_2, y_2, z_2)$ along a straight line, with the screw trajectory represented as a vector $A=[P_1,P_2]=[x_1,y_1,z_1,x_2,y_2,z_2]$.

Algorithm 1 Algorithm for selecting the start and end points of the screw trajectory

Input：The 3D bone model and the screw trajectory are located in a straight line L . Let a moving point on the line L be $P_0(x_0,y_0,z_0)$.

Output：The start point $P_1(x_1,y_1,z_1)$ and end points of the screw trajectory $P_2(x_2,y_2,z_2)$.

Load Image
for z_0 :max→min
  for x_0, y_0 ： $(x_0,y_0,z_0)\in L$
    if $(x_0,y_0,z_0)\in$ subchondral bone: Record this point as P'
    if $(x_0,y_0,z_0)\in$ femoral head && $d((x_0,y_0,z_0),P')\in[2,3]$ mm: $P_2=P'$
    if $(x_0,y_0,z_0)\in$ femoral: Record this point as P''
$P_1=P''$

(2) Fitting methods for different bone structures and determination of the axes of the fitted 3D model

During surgery, the screw trajectory's start point is in the femoral head edge, passing through the epiphyseal edge of the femur, and ending in the femur. To account for the consistency of body structures and the doctor's experience, this study employs different fitting methods based on the unique characteristics of various bone structures.

Cylindrical Fitting method

The segment of the screw trajectory within the femoral structure should pass through the femur as much as possible and be centered in the femoral neck for enhanced screw robustness. The femoral neck is approximated as a cylinder in the 3D model, with the most stable straight line passing through it being the mid-axis. As shown in **Figure 3**, a cylinder fitting method is used to approximate the femoral neck and part of the femur as cylindrical. The optimal screw trajectory, when considering only the femoral structure, is expected to intersect from this mid-axis. This mid-axis serves as the reference line for determining the start point $P_{F1}(x_1,y_1,z_1)$ and end point $P_{F2}(x_2,y_2,z_2)$ of the screw trajectory using Algorithm 1. The resulting line segment is considered the optimal screw trajectory $A_F=[P_{F1},P_{F2}]=[x_1,y_1,z_1,x_2,y_2,z_2]$ when considering only the femoral structure.

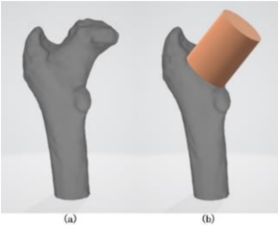

Figure 3. The cylinder fitting schematic. (a) Diagram of the Femur, (b) Cylinder Fitted

Spherical Fitting Method

The femoral head is almost entirely surrounded by the femur's epiphyseal edge and subchondral bone, as shown in **Figure 4**(a). Consequently, this study interprets the requirements of the femoral head for the screw trajectory as equivalent to those of the femur's epiphyseal edge and subchondral bone. This adaptation ensures that the screw trajectory is optimized to meet the specific needs of these critical anatomical structures, which are vital for the stability and function of the hip joint.

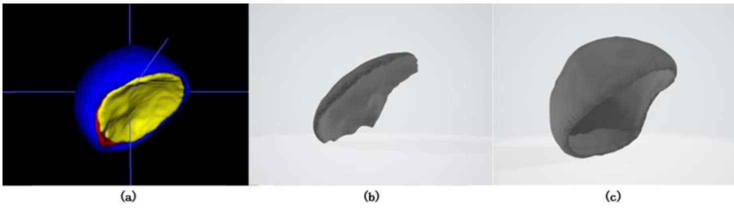

Figure 4. (a) The femoral head obtained after image segmentation, blue represents the subchondral bone, yellow represents the epiphyseal edge of the femur, and red represents the femoral head. (b) 3D display of the epiphyseal edge of the femoral head. (c) 3D presentation of subchondral bone

In three-dimensional space, the femoral head's epiphyseal edge and subchondral bone exhibit significant spherical characteristics, suggesting that the femoral head can be approximated by a figure enclosed by two spheres. Therefore, this study fits the epiphyseal edge (**Figure 4** (b)) and subchondral bone (**Figure 4** (c)) as spherical surfaces, respectively, extracting the center of the sphere from the center of the spherical surface. The optimal screw trajectory is considered to be the line where the corresponding points of the two spheres lie. The optimal screw trajectory for the epiphyseal edge is obtained by Algorithm 1 and denoted as $A_{EE} = [P_{EE1}, P_{EE2}] = [x_1, y_1, z_1, x_2, y_2, z_2]$, starting at $P_{EE1}(x_1, y_1, z_1)$ and ending at $P_{EE2}(x_2, y_2, z_2)$. Similarly, the optimal trajectory for the subchondral bone is denoted as $A_{SB} = [P_{SB1}, P_{SB2}] = [x_1, y_1, z_1, x_2, y_2, z_2]$, also starting at $P_{SB1}(x_1, y_1, z_1)$ and ending at $P_{SB2}(x_2, y_2, z_2)$. As an example, CT images from a patient were used to pre-design the screw trajectory for the extracted bone features, with the results shown in **Table 1** and illustrated on a 3D bone model in **Figure 5**.

Table 1. Pre-design results of a patient's screw trajectory

Screw trajectory	Pre-design Results
$A_F = [P_{F1}, P_{F2}] = [x_1, y_1, z_1, x_2, y_2, z_2]$	[125,258,62,75,264,138]
$A_{EE} = [P_{EE1}, P_{EE2}] = [x_1, y_1, z_1, x_2, y_2, z_2]$	[97,240,111,76,260,140]
$A_{SB} = [P_{SB1}, P_{SB2}] = [x_1, y_1, z_1, x_2, y_2, z_2]$	[103,244,109,75,264,141]

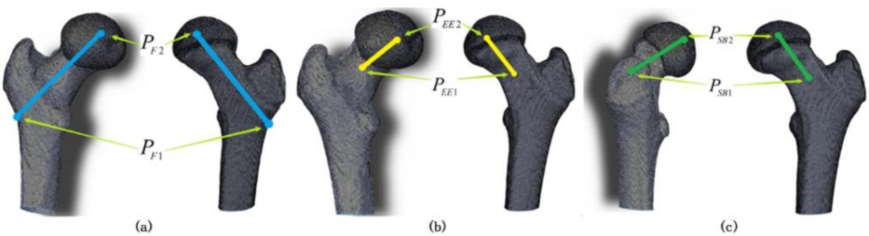

Figure 5. Schematic representation of the optimal screw trajectory considering only (a) the femur, (b) epiphyseal edge of the femur, and (c) subchondral bone (left and right sides of each figure are shown in different views)

(3) Pre-design results of screw trajectory range parameters

By joining the start points of the three screw trajectories P_{F1}, P_{EE1}, P_{SB1}, we define the enclosed region as $\alpha(A_{F1}, A_{EE1}, A_{SB1})$. Connecting the end points defines the enclosed region $\beta(A_{F2}, A_{EE2}, A_{SB2})$, see the plane α as the base of a triangular cone, and see the plane β as the top of a triangular cone, and determine a prismatic region. We consider that the line where the selectable screw trajectory is located should pass through the planes α and β, and the start and end points of the screw trajectory are obtained through Algorithm 1. All trajectories meeting these criteria are considered feasible. The tri-prism formed by these trajectories is the result of pre-designing the screw trajectory range parameters. The optimal screw trajectory range, derived from multiple pre-designed solutions, is shown in **Figure 6**.

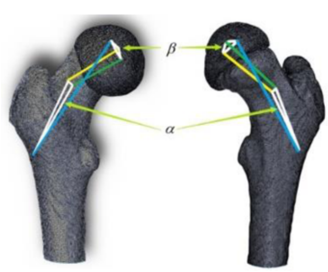

Figure 6. Pre-designed range of screw trajectory parameters (left and right sides are shown in different views)

3.3. Optimal screw trajectory selection results

(1) Design of screw trajectory evaluation indicators

In SCFE surgery, the screw trajectory starts in the femur, passes through the epiphyseal plate and femoral head edge, and ends in the femoral head. Titanium alloy screws, known for their high density and modulus of elasticity, act as connectors between the femoral head and neck, resisting forces from various directions. This supports preventing further slippage and complications. Focusing on the femur, epiphyseal edge, and femoral head, this study discusses evaluation indices for the screw trajectory. The evaluation indicators are presented in **Table 2**, with weights in **Tables 2-5** determined by orthopaedic surgeons from Beijing Jishuitan Hospital.

Table 2. screw trajectory evaluation indicators S

Evaluation indicators	Symbol	Indicator weights	Weighting values
Femoral-focused	S_F	ω_F	40%
Epiphyseal-edge-of-the-femur-focused	S_{EE}	ω_{EE}	30%
Femoral-head- focused	S_{FH}	ω_{FH}	30%

To assess the screw trajectory for different bone structures, key factors are considered. The contact area between the trajectory and bone structure is crucial as it affects the force on the fixation screws. Additionally, the deviation between the actual trajectory and the pre-designed optimal trajectory is evaluated. The screw trajectory evaluation indicators for the femur S_F are presented in **Table 3**, with their respective weights set as ω_F . The screw trajectory evaluation indicators focusing on the epiphyseal edge of the femoral head S_{EE} are shown in **Table 4**, and their weights are set as ω_{EE} .

Table 3. Femoral-focused screw trajectory evaluation indicators S_F

Evaluation indicators	Symbol	Indicator weights	Weighting values
Length of the screw trajectory in the femur	l_F	ω_{F-l}	66.6%
Angle between the screw trajectory and A_F	θ_F	$\omega_{F-\theta}$	16.7%
Spatial distance between the screw trajectory and A_F	d_F	ω_{F-d}	16.7%

Table 4. Epiphyseal-edge-of-the-femur-focused screw trajectory evaluation indicators S_{EE}

Evaluation indicators	Symbol	Indicator weights	Weighting values
Length of the screw trajectory in the epiphyseal edge of the femoral head	l_{EE}	ω_{EE-l}	33. 4%
Angle between the screw trajectory and A_{ME}	θ_{EE}	$\omega_{EE-\theta}$	33.3%
Spatial distance between the screw trajectory and A_{ME}	d_{EE}	ω_{EE-d}	33.3%

The screw trajectory evaluation indicators for the femoral head S_{FE} are shown in **Table 5**, with weights set as ω_{FE} . The femoral head's demand for a screw trajectory is translated into the requirements of the femur's epiphyseal edge and subchondral bone, considering that the screw trajectory versus A_{EE} variability has been introduced into the evaluation indicator S_{EE} , the variability of the screw trajectory versus A_{SB} is introduced as S_{FH} . In summary, the evaluation indicators designed in this study are shown in **Figure 7**.

Table 5. Femoral-head-focused screw trajectory evaluation indicators S_{FH}

Evaluation indicators	Symbol	Indicator weights	Weighting values
Length of the screw trajectory in the femoral head	l_{FH}	ω_{FH-l}	50%
Angle between the screw trajectory and A_{SB}	θ_{SB}	$\omega_{SB-\theta}$	25%
Spatial distance between the screw trajectory and A_{SB}	d_{SB}	ω_{SB-d}	25%

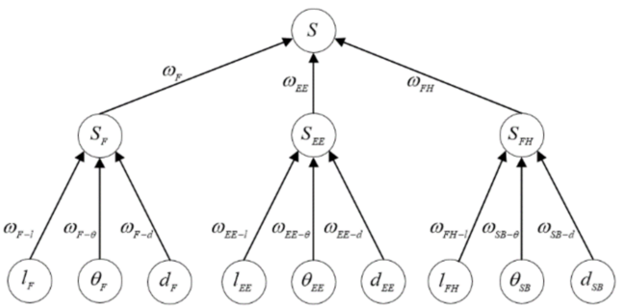

Figure 7. Screw trajectory evaluation indicators

(2) Calculation of screw trajectory score

Prior to calculating screw trajectory scores, data normalization is necessary to standardize the original data using Min-Max normalization, which scales the data to the range [0, 1]. The Min-Max normalization formula is given by Eq. (1), where x is the original data, $x_{\min}$, $x_{\max}$ are the maximum and minimum values, respectively.

$$x_{nom} = \frac{x - x_{\min}}{x_{\min} - x_{\min}} \tag{1}$$

After normalization, the screw trajectory scores were calculated using a weighted summation method, with weights assigned by a professional orthopaedic surgeon. The formulas for calculating the scores of the screw trajectory evaluation indicators for a specific bone structure and the total score are provided in Eqs. (2) and (3), respectively. Upon completing the calculation, the scoring result of the screw trajectory is obtained, providing a quantitative measure of its quality. This helps in further selecting optimal solutions for the screw trajectory in this study.

$$S_i = \sum_j x_j \omega_j \tag{2}$$

$$S = \sum_i S_i \omega_i \tag{3}$$

(3) Optimal Screw Trajectory Selection Method Based on Genetic Algorithm

Coding rules: Fixed-length binary coding is employed, with the screw trajectory treated as a chromosome. The three-dimensional coordinates $x_1', y_1', z_1', x_2', y_2', z_2'$ of the intersection of the screw trajectory $A=[x_1,y_1,z_1,x_2,y_2,z_2]=f\left(x_1',y_1',z_1',x_2',y_2',z_2'\right)$ with α,β respectively, a total of six data, after binary coding, are used as the genes composing the chromosome, and the genes are restricted by the requirement that $x_1',y_1',z_1'\in\alpha$, $x_2',y_2',z_2'\in\beta$.

Initial population formation: A random approach was used to create an initial population of 20 screw trajectories, selected from the pre-designed range parameters in section ***3.2*(3)**.

Population fitness: screw trajectory scores, calculated using the evaluation indicators and scoring method from sections ***3.2*(1)** and ***3.2*(2)**, respectively, are used as fitness values. Higher-scoring trajectories have higher fitness.

Crossover and Mutation Algorithm: crossover probability is set to 0.8, and mutation probability to 0.05. Individuals with a 0.8 probability will crossover with others, and a 0.05 probability will mutate (perform a binary inversion).

The algorithm continues with crossover and mutation until the specified number of evolutionary generations is reached. If the number is not reached, the process continues; otherwise, the individual with the highest fitness is chosen as the result, which is the optimal screw trajectory.

The optimal screw trajectory is designed for a patient by the above method, and the optimal result is $A=[P_1,P_2]=[x_1,y_1,z_1,x_2,y_2,z_2]=[129,254,81,75,262,141]$, which is shown schematically in relation to the pre-design range of the screw trajectory parameters in **Figure 8**.

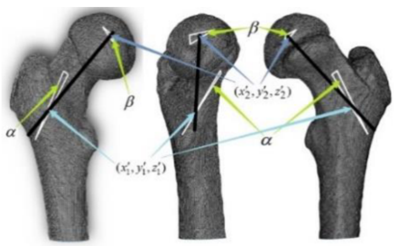

Figure 8 . Optimal screw trajectory results

4. Discussion

To determine the optimal screw trajectory for SCFE surgery, this study segmented bone features from CT data of actual Beijing Jishuitan Hospital patients, including femur, femoral head, epiphyseal edge, and subchondral bone. An algorithm was developed based on physician guidance to derive the optimal trajectory parameters. Evaluation indicators and a scoring method were established to assess screw trajectory designs. The genetic algorithm was then employed to find the optimal trajectory, effectively integrating medical expertise with algorithmic precision. This hybrid approach enhances the customization and accuracy of the surgical plan, leading to improved patient outcomes and procedural efficiency.

Precise bone feature segmentation and 3D model creation are crucial for surgical planning and screw trajectory design. This study used nnU-Net to achieve outstanding results in segmenting the femur and femoral head from preoperative 3D CT data. The segmentation performance was comparable to that reported by Li et al. for cardiac tissue segmentation in cardiac CTA images[5]. Although segmentation of subchondral bone and the femoral head epiphyseal edge was slightly less accurate, these structures are less prominent in CT images. Nevertheless, the robust segmentation effectively characterized the surgical region, providing a strong foundation for subsequent planning steps.

To facilitate screw trajectory pre-design, this study introduces a method to identify the straight line trajectory across bone structures and an algorithm to calculate its start and end points. For subchondral bone and femoral head epiphyseal edge, the method provides locally optimal trajectories aligned perpendicular to the epiphyseal plane[13]. For the femur, the trajectory is optimized for screw fixation and load-bearing capacity[14]. These optimal trajectories are combined into a prismatic region, expanding viable screw paths and force distribution. This pre-setting scheme sets the scope for optimization and provides a framework for trajectory evaluation indicators. The approach ensures a well-founded and adaptable surgical strategy tailored to each patient's unique anatomy.

Research suggests that for mild SCFE, there's no significant difference in fixation outcomes between perpendicular and non-perpendicular screw trajectories through the epiphyseal plate[15]. However, with increasing slippage, the risk of the screw path exiting the femur increases if the trajectory is strictly perpendicular[16]. In moderate cases, inclined screw implantation is superior to perpendicular insertion[14]. This study, therefore, goes beyond the sole consideration of perpendicular angles and incorporates additional factors based on the femoral head and femur's three-dimensional structure and spatial position. This enhances the realism and clinical applicability of the screw trajectories designed, ensuring that the surgical plans are not only anatomically precise but also consider the practical implications of varying degrees of slippage on screw placement and fixation stability.

This method designs screw trajectories from pre-operative 3D CT data, reducing radiation risks compared to traditional surgery's repeated fluoroscopy. It's a breakthrough for patient and surgeon safety, with ethical considerations allowing surgeons to adjust plans as needed. Clinicians at Beijing Jishuitan Hospital have reviewed and validated the approach. However, the study has limitations, including potential viable trajectories outside the defined range and the complexity of severe cases requiring multiple screws. Further refinement and expansion of the method are necessary to cover diverse SCFE cases.

Acknowledgement

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