


## CLINICAL ARTICLE

# Crowe Type IV Hip Dysplasia Treated by THA Combined with Osteotomy to Balance Functional Leg Length Discrepancy: A Prospective Observational Study

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**Objective:** To measure the factors that affect functional leg length of Crowe type IV Developmental dysplasia of the hip (DDH) patients and to review our own methods to balance leg length discrepancy (LLD) in Crowe type IV DDH patients.

**Methods:** This was a prospective observational study which started in June 2017 and ended in August 2019. Inclusion criteria included: (i) Crowe type I or Crowe type IV hip dysplasia patients who underwent total hip arthroplasty (THA) in the Department of Orthopaedics at our institution between July 2017 and June 2018; (ii) the patients were treated with our specific leg length balance strategy; and (iii) the related outcomes of patients were completely recorded. Finally, 18 consecutive Crowe type I patients (20 hips) and 14 consecutive Crowe type IV patients (18 hips) were selected and divided into two groups according to Crowe types. All patients received THA, and patients with a longer affected side and inferior anatomical acetabular positions in Crowe type IV group also received subtrochanteric osteotomy. During operation and after hip reduction, leg lengths were compared while two legs were in an extended position and the operative leg was on top of the non-operative one. Additional leg length adjustment was applied when leg length was considered to be unequal. Prior to surgery, subluxation height of the femoral head on the affected side, functional LLD, bony length of lower limbs, and distance from teardrops to the lowest point line of the sacroiliac joint were recorded. After surgery, cup sizes, functional LLD, and height of hip rotational centers were measured. Clinical evaluations, such as Harris Hip Score (HHS) and SF-12 scale, were also obtained before and after surgery for all patients.

**Results:** At the last follow-up, functional LLD and clinical measurements of both Crowe type IV group and Crowe type I group were significantly improved. Compared with Crowe type I patients, Crowe type IV patients had a significantly lower MCS, a significantly longer leg lengthening length and a significantly lower hip center height after surgery. Significant differences of tibia length, leg length, and teardrop position were found between affected side and healthy side of Crowe type IV patients. Only three of 14 Crowe type IV patients remained under 1 cm functional LLD. Five patients in the Crowe type IV group developed lower limb numbness immediately following surgery, and they all recovered within 6 months. The average follow-up period for either group was 14 months, and all patients were followed-up at 1, 3, 6, and 12 months then yearly after surgery until the final follow-up.

**Conclusion:** After detailed leg length balance process, THA combined with transverse sub-trochanter osteotomy could be an effective method to achieve equal function leg length with most Crowe type IV patients.

**Key words:** Hip dislocation; Leg length inequality; Osteotomy; Skeletal deformity; Total hip replacement

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## Introduction

Hip dysplasia is a common reason for which patients undergo total hip arthroplasty (THA). There are various malformations in the pelvises and femurs of hip dysplasia patients, such as shallow acetabular, small femoral medullary, enlarged combined anteversions, and others. These malformations are particularly severe in Crowe type IV hip dysplasia patients<sup>1,2</sup>. THA is an effective method to treat Crowe type IV hip dysplasia and has demonstrated excellent clinical results<sup>3,4</sup>. However, leg length discrepancy can often become one of the most common post-surgical complications in Crowe type IV hip dysplasia patients. Recently, we found that hip dysplasia patients who underwent THA placed growing attention on leg length discrepancy (LLD) post-surgery, and these have become some of the primary sources of patient dissatisfaction with surgery. There is also research indicating that post surgery LLD affects hip function and psychological status of hip dysplasia patients<sup>5,6</sup>.

Nowadays, it is a generally held consensus that the hip rotational center should be reconstructed at its anatomical position for Crowe type IV Developmental dysplasia of the hip (DDH) patients. However, highly dislocated femoral head and severe peri-joint soft tissue contracture render hip reduction a difficult process, and excessive leg lengthening is considered to be one of the main reasons causing post-THA nerve injury. Due to this, Charnley firstly introduced osteotomy to aid in the hip reduction process with highly dislocated dysplasia hips<sup>7</sup>. Then, various osteotomy techniques have been developed such as: transverse osteotomy<sup>8</sup>, oblique osteotomy<sup>9</sup>, Z-shaped osteotomy<sup>10</sup>, and V-shaped osteotomy<sup>11</sup>. With certain osteotomy techniques, hip reduction of Crowe type IV DDH hips could be considered more trivial, and nerve injury rates were reported to range from 5% to 11.3%<sup>12</sup>. However, many osteotomy methods reduce leg length, and with excessive osteotomy, achieving equal leg length post-surgery for Crowe type IV DDH remains difficult.

Several non-osteotomy THA techniques were introduced, such as setting femoral osteotomy lines as low as possible, using powerful muscle relaxation medications<sup>13</sup>, or using a Hohman retractor to help reduction<sup>14</sup>. Compared to THA combined with osteotomy, non-osteotomy techniques are widely considered to not sacrifice leg length. Furthermore, no severe nerve complications were reported in this research. However, some research has found that, except for highly dislocated femoral head, bony leg length discrepancy and malformation of the pelvis also affect post-surgery leg length of Crowe type IV DDH patients. With the line connecting the apexes of the iliac wings; the line through the acetabular teardrops; the line connecting the inferior sacroiliac joints; and the line connecting the lowest points of the ischial tuberosity, Bilgen *et al.* divided pelvic dysplasia into three areas. They found that the teardrop's position on the affected side was 1.056 mm more distal than that of the contralateral side with Crowe type IV patients<sup>15</sup>. Zhang *et al.* measured lesser trochanter-tibial plafond distance of 67 unilateral DDH patients (32 Hartofilakidis type II and

35 Hartofilakidis type III) and found that lesser trochanter-tibial plafond distance on the affected side was on average 10 mm longer than that on the contralateral side in 78% of the patients<sup>16</sup>. Compared to a healthy hip, after anatomical hip rotational center reconstruction, a more inferior anatomical acetabular position combined with a longer leg in bony length could easily lead to an obvious longer functional leg length of the operated side after THA. In this condition, osteotomy should be considered, not only to aid in hip reduction, but also to help balance functional leg length. However, few studies have taken all these factors into account, and little research has examined the position of acetabular cup after surgery relative to its original anatomical position with Crowe type IV DDH patients.

Li *et al.*<sup>17</sup> described a lower limb balance strategy for Crowe type IV DDH patients in detail in 2017. According to unilateral side or bilateral side DDH, they divided patients into type I (unilateral) or type II (bilateral), and patients are further subdivided into three subtypes according to pelvic oblique and fixed spinal curvature. If there were no bony LLD, this was noted for patients without pelvic obliquity to balance functional LLD or anatomical LLD; for patients with compensatory pelvic obliquity, they noted that to balance anatomical LLD is optimal; for patients with fixed pelvic tilt and spinal curvature, they noted to balance functional LLD. In their research, there was an overall significant bony LLD of 3.5 mm, however, they concluded that it had little clinical significance, besides they did not take pelvic malformation into consideration.

The purposes of this study were: (i) to determine whether, after elaborate preoperative planning and leg length balancing during operation, THA combined with transverse sub-trochanter osteotomy is an effective method to achieve equal function in leg length with Crowe type IV patients; (ii) to determine whether the relative position of the acetabular cup affected leg length in Crowe type IV hip dysplasia patients; (iii) to compare short-term clinical evaluations (Harris Hip Score and SF-12 scale) and radiology measurements (subluxation height of the femoral head on the affected side, bony length of lower limbs, and distance from teardrops to the lowest point line of the sacroiliac joint were recorded) between or within the Crowe type IV DDH patient group and Crowe type I patient group.

## Methods and Materials

### Inclusion and Exclusion Criteria

Inclusion Criteria included: (i) Crowe type I or Crowe type IV hip dysplasia patients who underwent THA in the Department of Orthopaedics at our institution between July 2017 and June 2018; (ii) the patients were treated with our specific leg length balance strategy; and (iii) the related outcomes of patients were completely recorded.

Exclusion criteria included: (i) a history of pelvic trauma; (ii) previous pelvic surgery; (iii) history of hip infection or tumor; (iv) absence of any necessary patient data;

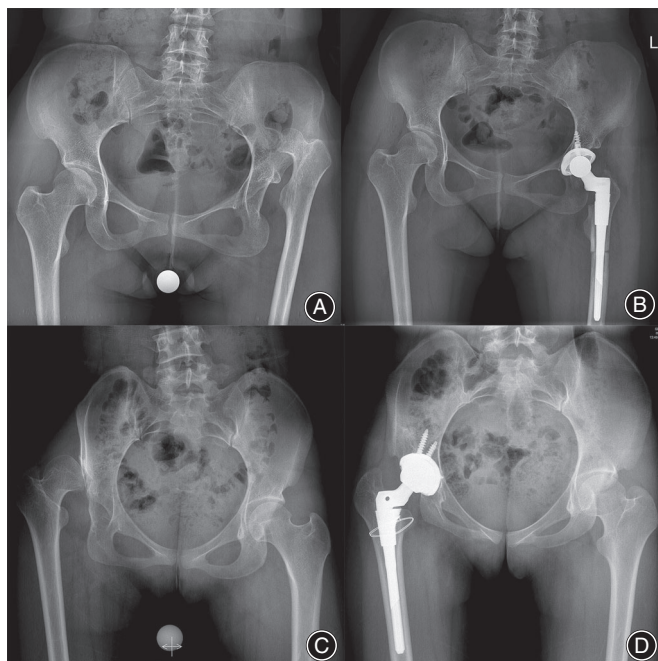
(v) any patients who had unilateral or bilateral other-Crowe-type forms of hip dysplasia; (vi) lumbar spine stiffness (lumbar spine lateral curve  $<15^\circ$ ) or severe spinal deformity.

### Group Allocations

Two groups of patients were included in this study: 14 consecutive Crowe type IV hip dysplasia patients (17 hips) who underwent THA during July 2017 to June 2018 were defined as group A; whereas group B consisted of 18 consecutive Crowe type I hip dysplasia patients (20 hips) who underwent THA during the same time period.

### Preoperative Planning

Surgery for all patients aimed to reconstruct the rotation center at its anatomical position. During preoperative planning, leg length balance was considered as follows: after anatomical acetabular reconstruction, LLD caused by femoral head dislocation is diminished. Besides bony LLD with a longer affected side and inferior anatomical acetabular positions indicated applications of osteotomy, subtrochanteric osteotomy should also be determined during THA process according to the degree of hip reduction difficulty. Finally, leg length comparison should be completed after reduction, and any necessary further adjustment of leg length should be executed such as additional osteotomy and adjustment of femoral head size. For bilateral patients, osteotomy is determined only according to degree of hip reduction difficulty



**Fig. 1** Anteroposterior pelvic radiograph of two CROWE IV patients underwent THA with or without osteotomy. Pictures A and B belong to one patient underwent THA with osteotomy and pictures C and D belong to another patient underwent THA without osteotomy.

with the first side of bilateral patients, osteotomy is considered when hip reduction is difficult and leg length comparison is unnecessary.

### Operation Process

All THA were completed by the same senior professor at our institution with the patients under general or epidural anesthesia. Patients were placed in a lateral position and a posterolateral approach was applied in all cases. Because true acetabula in group A patients were consistently shallow and small, we consequently reamed them at a posterior and superior direction in order to enlarge the acetabular and gain enough cup bony coverage while reserving as much anterior acetabular bone as possible<sup>18</sup>. On the femoral side, cementless modular femoral components (Depuy S-ROM) were employed for all patients in group A, and cementless monoblock stems were employed for all patients in group B. The combined anteversion of all patients were set under  $55^\circ$  to prevent post-surgery dislocation<sup>19</sup>. Specific soft tissue release can vary widely and relate to the hip capsule, iliotibial tract, part of gluteus, the adductor, iliopsoas muscle, sartorius muscle, and rectus femoris<sup>20</sup>.

For patients with a longer affected side and inferior anatomical acetabular positions in group A, we routinely applied transverse subtrochanteric osteotomy. For patients who underwent subtrochanteric osteotomy, after the first cut at the proximal femur, we physically pulled the affected limb until it was the same length as the other, then the overlapped part was removed. For patients without bony LLD and inferior anatomical acetabular positions in group A, we applied osteotomy unless reduction was impossible (Fig. 1). For patients in group B, we applied no osteotomy. Patients in group B have no inferior anatomical acetabular position, unless some of them have mild longer affected limbs. According to our experience, these mild bony LLD could be easily corrected by THA without osteotomy.

After hip reduction, leg lengths were compared while two legs were in an extended position and the operative leg was on top of the non-operative one. If the heels of two legs were at same position, leg lengths were considered to be equal. If the leg lengths were not equal, adjustment of femoral head size and additional osteotomy were used as final leg length adjusting measures. Reduction was completed while the hip flexed at  $60^\circ$  with an abduction of  $20^\circ$  and the knee flexed with an internal rotation of  $90^\circ$ , as described by Yan *et al.*<sup>13</sup>. During the reduction process, our attending surgeon palpated soft tissue around the sciatic nerve to ensure its tension was acceptable according to his experience. Equal leg length should not be considered when the safety of sciatic nerve is in question.

### Clinical Evaluation

All patients underwent an initial clinical evaluation on the first day after hospitalization and last clinical evaluation during their final follow up.

### Harris Hip Score (HHS)

The HHS is a widely used method to evaluate hip function and was used before and after THA for all patients in this study. The HHS score system comprises of four aspects including pain, function, absence of deformity, and range of motion. The score standard had a maximum of 100 points (best possible outcome). A total score <70 is considered a poor score, with 70–80 being fair, 80–90 being good, and 90–100 being excellent.

### SF-12 Scale

SF-12 Scale is a multipurpose, short-form generic measure of health status that is used world-wide<sup>21</sup>. With this instrument, Physical Component Summary (PCS) and Mental Component Summary (MCS) could be obtained to evaluate physical and mental health status of patients, respectively. Both PCS and MCS are considered to be better with a higher score.

### Measurement of Radiology

All measurements were taken with TraumaCad 2.0 software (Orthocrat LTD. Ltd.2007).

### Femoral Head Dislocation Height

For DDH patients, femoral head dislocation height refers to the distance which affected femoral head moved upwardly. Prior to surgery, femoral head dislocation height was measured on the pelvic anteroposterior pelvic radiographs (APs) for all patients. For unilateral patients, femoral head subluxation height was calculated by subtracting the vertical distance from apex of lesser trochanter to the teardrop line on the healthy side from the affected side (Fig. 2); for bilateral patients, this measurement was considered to be the distance between the head–neck junction to the teardrop line for each side. In general, a femoral head dislocation height is considered to be severely high when it is not lower than 3.5–4 cm.

### Leg Length

Femur length, tibial length, and bony leg length refer to length of femur, tibia, and the whole leg, respectively, that are measured on full leg length radiographs of DDH patients.

For unilateral patients, leg length was measured for both sides, including femur length (top of femoral head to midpoint of femoral condyles), tibial length (inter-condylar eminence of tibia to midpoint of the tibial plafond) and bony leg length (tip of lesser trochanter to midpoint of the tibial plafond) (Fig. 3)<sup>15</sup>. Negligence of significant differences of leg length between two sides could lead to functional LLD after THA.

### Teardrop Position

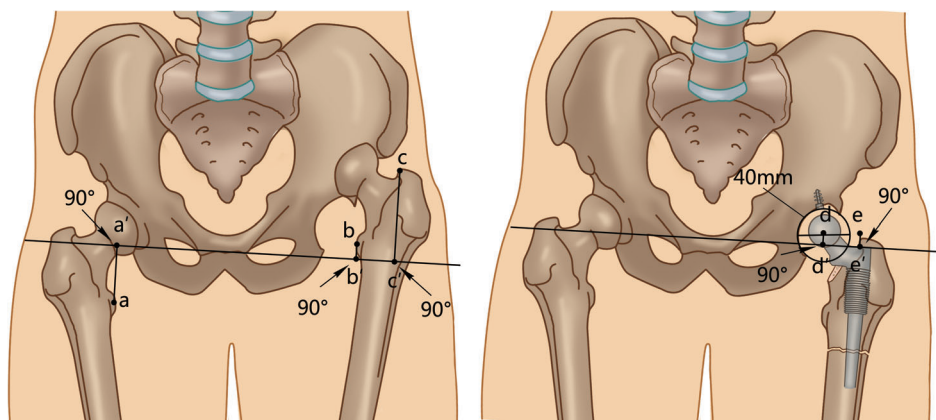
Teardrop position refers to the height of teardrop on the pelvic APs. For unilateral patients, we also measured the distance from the teardrops to the lines that connected most inferior points of sacroiliac joints for healthy and affected sides, respectively (Fig. 4). Teardrop position indicates the original position of acetabulum and an inferior acetabular position compared with the healthy side can lead to a longer functional leg length after THA.

### Leg Lengthening

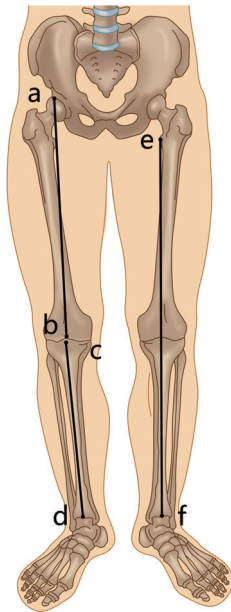
For DDH patients, leg lengthening refers to the distance which affected leg lengthened after THA. Affected leg lengthening length was considered to be the distance that the greater trochanter migrated inferiorly from the pre-operation to post-operation positions, and the measurement method is showed in Fig. 2<sup>17</sup>. Affected legs of Crowe type IV DDH patients are considered to have a risk of nerve damage while it is lengthened up to 3.5–4 cm.

### Hip Center Height

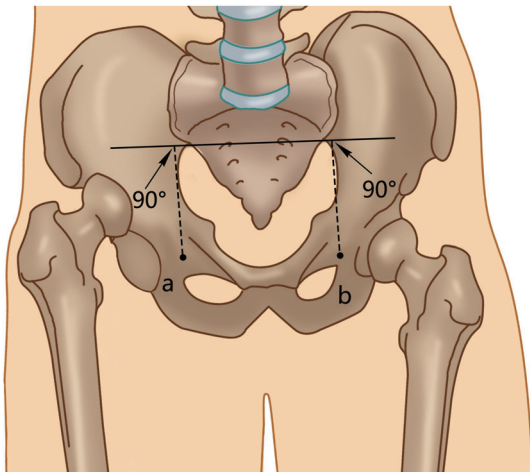
Hip center height refers to the height of cup center or femoral head center after THA. After surgery, hip center height was measured as the distance from the hip rotational center to the teardrop line for all affected hips, which are shown in Fig. 2<sup>22</sup>. Hip center height for Crowe type IV DDH patients could be a potential factor which affects leg length notably after THA.



**Fig. 2** Schematic diagrams showing measurement of femoral head dislocation height, leg lengthening and hip center height. The transverse lines are teardrop lines. a and b are tips of lesser trochanters of two sides; c and e are tips of greater trochanter of affected side before and after THA respectively; d is the cup or femoral head center. Before surgery, femoral head dislocated height =  $aa' + bb'$ . After surgery, leg length lengthening =  $ee' - cc'$ . Used cup size was 40 mm, hip rotational center height =  $dd'$ .



**Fig. 3** A schematic diagram showing measurement of leg length. A is top of femoral head, B is midpoint of femoral condyles, C is intercondylar eminence of tibial, D and F are midpoints of the tibial plateaus, E is tip of lesser trochanter. Thus, AB is representative of femur length; CD is representative of tibial length; EF is representative for bony leg length.



**Fig. 4** A schematic diagram showing measurement of teardrop position. The transverse line in this diagram is the line that connected most inferior points of sacroiliac joints, A and B are teardrops of affected side and healthy side respectively. Thus the two dashed vertical lines to the transverse line represent teardrop positions of two sides.

#### Statistical Analysis

SPSS19.0 software (IBM Corporation, NY, USA) was used for statistical description and analysis of data. All parameters

and outcomes in this study are quantitative in nature. Measurement data were consistent with normal distributions described by mean  $\pm$  standard deviation ( $\bar{x} \pm s$ ); paired sample t-tests were used for intra-group comparison (including HHS, SF-12 PCS, SF-12 MCS, teardrop position, and all measurements of leg length), and independent sample t-tests were used for inter-group comparison (including age, height, weight, BMI, surgery time, HHS, SF-12 PCS, SF-12 MCS, cup size, and hip center height). Measurement data with non-normal distributions were described by P50 (P25-P75), and comparison between groups was conducted by the Mann-Whitney test (including follow-up period, osteotomy amount, femoral head dislocation height, functional LLD, and leg lengthening length).  $P < 0.05$  was considered statistically significant.

## Results

### Follow-Up

All patients were followed up at 3, 6, and 12 months and then yearly after surgery until the last follow-up. The follow-up period of group A and group B are 14.00 (12.75–18.25) months and 14.00 (12.75–14.25) months, respectively ( $P = 0.585$ ).

### General Results

Thirty-two patients were included in this study with 14 Crowe type IV patients (17 Crowe type IV dysplasia hips) allocated to group A and 18 Crowe type I patients (20 CROWE I dysplasia hips) allocated to group B. Basic information for the two groups is shown in Table 1. Average size of used cups of group A is significantly smaller than that of group B ( $44.82 \pm 3.32$  mm vs  $50.90 \pm 2.71$  mm,  $P < 0.001$ ); average surgery time of group A is significantly longer than that of group B ( $149.53 \pm 51.46$  vs  $103.40 \pm 25.71$ ,  $P = 0.010$ ).

For patients in group A, only seven legs received femoral osteotomy, and the mean osteotomy value was 1.16 cm overall. No osteotomy site nonunion occurred (Fig. 5).

### Radiographic Measurement

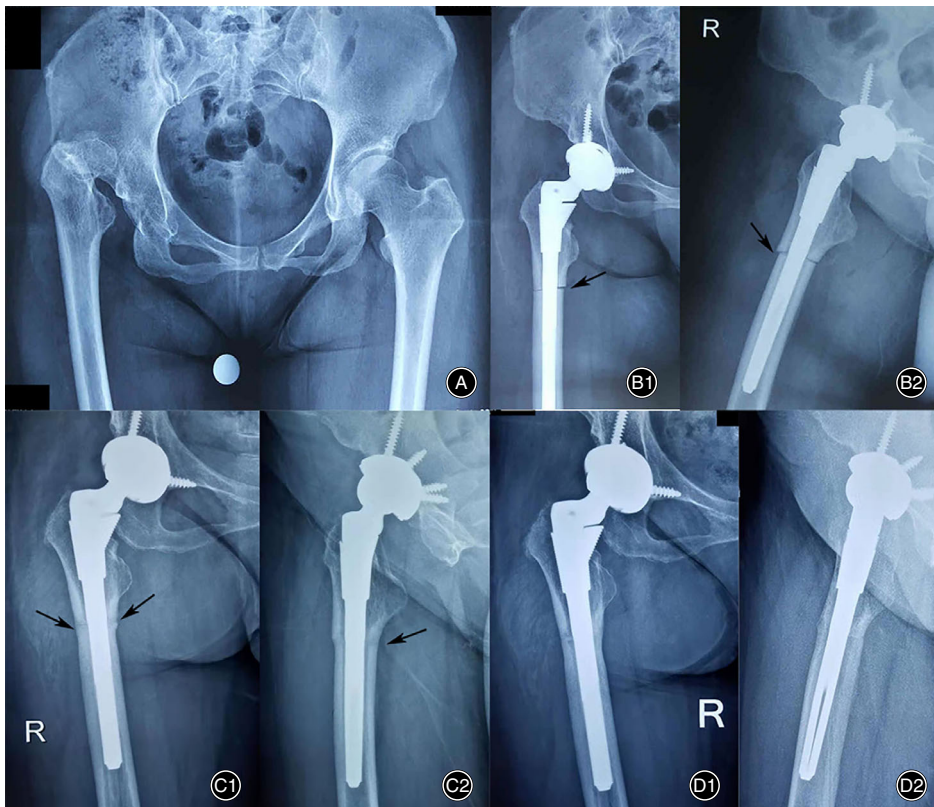
Before surgery, femoral head subluxation height was significantly larger for group A compared to group B ( $4.50$  [2.75–6.05] vs  $0.88$  [0.53–1.10],  $P < 0.01$ ). After operation, hip center height of group A was significantly lower than that of group B ( $14.20 \pm 5.02$  vs  $20.92 \pm 4.66$ ,  $P < 0.001$ ); leg lengthening length of group A was significantly longer than that of group B ( $2.70$  [2.50–4.10] vs  $0.6$  [0.40–0.80],  $P < 0.001$ ) (Tables 2 and 3).

For unilateral patients in both groups (11 of 14 patients in group A and 16 of 18 patients in group B), radiographic leg length and teardrop position measurements are shown in Table 4. For the same patients in group A, the tibial lengths and lower limb lengths of affected sides were significantly longer than those of healthy sides ( $33.92 \pm 2.09$  cm vs  $33.37 \pm 1.91$  cm,

**TABLE 1 Basic information of the two groups (mean±SD)**

Groups	Age (years)	Height (cm)	Weight (kg)	BMI (kg/m <sup>2</sup> )	Surgery time (min)	Cup size (mm)
Group A	44.29 ± 11.55	162.71 ± 5.32	64.36 ± 7.30	24.30 ± 2.45	149.53 ± 51.46	44.82 ± 3.32
Group B	55.89 ± 14.03	161.72 ± 3.80	62.89 ± 8.25	24.10 ± 3.48	103.40 ± 25.71	50.90 ± 2.71
P	0.018	0.340	0.953	0.985	0.010	<0.01

BMI, body mass index.



**Fig. 5** A series of plain X-ray photographs of one Crowe IV patient received subtrochanter osteotomy. Picture A is an anteroposterior pelvic radiograph before surgery. Pictures B, C and D are of the positive and lateral radiographs of the hip joint at 3 days after surgery, 6 months after surgery and 1 year after surgery. Arrows represent that the osteotomy site is visible, and at 1 year after surgery, the osteotomy site is a bony union.

**TABLE 2 Comparison of parameters between the two groups before surgery (mean±SD)**

Groups	HHS	SF-12 PCS	SF-12 MCS	Functional LLD (cm)	Dislocated height (cm)
Group A	57.53 ± 11.59	22.42 ± 15.58	20.68 ± 13.48	4.00 (3.00–5.00)	4.50 (2.75–6.05)
Group B	60.42 ± 12.66	15.38 ± 7.22	21.85 ± 10.24	0.90 (0.13–1.75)	0.88 (0.53–1.10)
P	0.477	0.099	0.783	<0.001	<0.001

HHS, Harris Hip Score; LLD, Leg Length Discrepancy; SF-12 MCS, Mental Component Summary; SF-12 PCS, physical component summary.

$P = 0.009$  and  $74.56 \pm 4.00$  cm vs  $73.71 \pm 4.31$  cm,  $P = 0.037$  respectively). The distance from the teardrop to the line connected to the most inferior points of the affected sacroiliac joint (teardrop position) was also significantly larger than that of healthy side ( $80.46 \pm 10.24$  mm vs  $76.71 \pm 9.18$  mm,  $P = 0.019$ ).

### Functional Evaluation

Compared with group A patients before surgery, functional LLD was improved significantly at the last follow-up (0 [0–0.08] vs 4.00 [3.00–5.00],  $P = 0.003$ ) (Table 5).

After surgery, HHS, SF-12 PCS, and SF-12 MCS were all significantly improved for both groups (for group A,

**TABLE 3 Comparison of parameters between the two groups after surgery (mean±SD)**

Groups	HHS	SF-12 PCS	SF-12 MCS	Functional LLD (cm)	Hip center height (mm)	Leg lengthening (cm)
Group A	89.82 ± 3.03	36.81 ± 15.17	37.96 ± 12.89	0 (0–0.08)	14.20 ± 5.02	2.70 (2.50–4.10)
Group B	90.40 ± 3.30	40.00 ± 10.03	46.15 ± 4.37	0 (0–0)	20.92 ± 4.66	0.6 (0.40–0.80)
P	0.586	0.480	0.038	<0.01	<0.01	<0.01

HHS, Harris Hip Score; LLD, Leg Length Discrepancy; SF-12 MCS, Mental Component Summary; SF-12 PCS, physical component summary.

**TABLE 4 Measurement of bony length and teardrop position of the two groups (mean±SD)**

Groups	GA:Femur length (cm)	GA:Tibia length (cm)	GA:Leg length (cm)	GA:Teardrop position (mm)	GB:Femur length (cm)	GB:Tibia length (cm)	GB:Leg length (cm)	GB:Teardrop position (mm)
Affected side	39.51 ± 2.52	33.92 ± 2.09	74.56 ± 4.00	80.46 ± 10.24	41.89 ± 2.14	34.43 ± 1.95	77.24 ± 3.81	71.48 ± 7.28
Healthy side	39.33 ± 2.85	33.37 ± 1.91	73.71 ± 4.31	76.71 ± 9.18	41.31 ± 2.23	33.96 ± 1.92	76.62 ± 3.76	70.41 ± 7.39
P	0.485	0.009	0.037	0.019	0.214	0.185	0.145	0.289

GA, Group A; GB, Group B.

$P < 0.001$ ,  $P = 0.039$ ,  $P = 0.007$  respectively; for group B, all three  $P$  values under 0.001), and these results are shown in Table 5. However, we found no significant difference of HHS, SF-12 PCS, and SF-12 MCS between the two groups before operation and only SF-12 MCS of group B was significantly higher than that of group A ( $46.15 \pm 4.37$  vs  $37.96 \pm 12.89$ ,  $P = 0.038$ ) after operation (Tables 2 and 3).

### Complications

Five patients in group A developed lower limb numbness immediately following surgery, and they all recovered within 6 months. No symptoms of motor nerve impairment occurred. At the last follow up, functional LLDs for the three patients were 0.3, 0.5, and 1.0 cm. For the patients with 0.3 and 0.5 cm functional LLD, no other treatment measures were needed; for the patient with a 1.0 cm functional LLD, shoe lift was recommended to improve limb function. No other complications occurred during THA and follow-up period.

### Discussion

#### Balance of Functional LLD

For Crowe type IV DDH patients, there could be many LLD definitions, such as bony LLD, functional LLD, and anatomical LLD<sup>17</sup>. Therefore, choosing optimal LLD to balance is a careful process. After taking bony LLD and pelvic malformation into consideration, we reason that functional LLD is the most appropriate LLD to balance, and we agree that with bilateral Crowe type IV DDH patients, the same femoral procedure is important. There are several reasons for choosing functional LLD to balance in our study. First, after

functional LLD balance, patients could have a high degree of satisfaction of leg length after surgery at once, because functional LLD is the length they wanted with the affected leg. Second, after taking bony LLD and pelvic malformation into consideration, and completed balance of functional LLD, the line connected to the most inferior points of the sacroiliac joint would be horizontal, which generally led to the most appropriate positions of lumbar vertebrae. And if there are no bony LLD and pelvic malformations or these factors have little influence, the functional LLD is almost equal to femoral head dislocated height, and this opinion is verified by Li *et al.*<sup>17</sup>. Third, with bony LLD and pelvic malformation, choosing femoral head dislocation height or bony LLD to balance is not only inaccurate and could lead to functional LLD post-surgery, it would also take a longer time for patients to adapt.

#### Osteotomy with THA

Although some research notes that osteotomies should be chosen when leg lengthening is more than 3.0–4.0 mm<sup>23</sup>, we opted to choose osteotomy according to operational conditions. The primary reason for choosing osteotomies is to protect against excessive stretching of the sciatic nerve. Although we agree that excessive stretching can be a primary factor in sciatic complications, the threshold of excessive stretching for high sciatic nerve complications rate remains unknown. On the other hand, in some studies lacking osteotomy, no permanent sciatic complication occurred<sup>13,14</sup>. Thus, in this study, we did not routinely applied osteotomy with all patients in group A. We considered osteotomy as one method to balance LLD unless reduction process was impossible during THA. As a result, only seven of 17 Crowe type

TABLE 5 Comparison of parameters between pre and post surgery (mean±SD)

Parameters	GA:HHS	GA:SF-12 PCS	GA:SF-12 MCS	GA:Functional LLD (cm)	GB:HHS	GB:SF-12 PCS	GB:SF-12 MCS	GB:Functional LLD (cm)
Pre-surgery	57.53 ± 11.59	22.42 ± 15.58	20.68 ± 13.48	4.00 (3.00–5.00)	60.42 ± 12.66	21.85 ± 10.24	15.38 ± 7.22	0.90 (0.13–1.75)
Post-surgery	89.82 ± 3.03	36.81 ± 15.17	37.96 ± 12.89	0 (0–0.08)	90.40 ± 3.30	40.00 ± 10.03	46.15 ± 4.37	0 (0–0)
P	<0.01	0.039	0.007	0.003	<0.001	<0.001	<0.001	0.003

GA, Group A; GB, Group B; HHS, Harris Hip Score; LLD, Leg Length Discrepancy; SF-12 MCS, Mental Component Summary; SF-12 PCS, Physical Component Summary.

IV hips received subtrochanteric osteotomy, and the overall mean osteotomy value was 1.16 (range, 0–3.7 cm). However, in this study, three patients in group A could not gain equal leg length at the final time of leg length comparison after reduction due to excessive tension of soft tissue. At the last follow-up, even these three patients maintained a functional LLD no more than 1 cm.

According to a previous study by Shi *et al.*<sup>24</sup>, post-operative LLD for Crowe type IV DDH patients are always around 10 mm. In our study, after a follow-up period of 14.0 (12.75–14.25) months, the functional LLD of Crowe type IV DDH patients was 0 (0–0.08). However, it is difficult to make a comparison between these studies as few researchers noted which types of LLD they measured in their research. According to Wang *et al.*<sup>12</sup>, nerve injury rates of Crowe type IV DDH patients after THA were reported to range from 5% to 11.3%. In our study, five hips from five different patients showed lower limb numbness immediately after surgery, and nerve symptom rate was up to 29.4%. However, all patients recovered within 6 months, and no symptoms of motor nerve impairment occurred. We reason that this is because only seven of 17 Crowe type IV hips received osteotomy, and the average osteotomy amount was relatively small.

#### Hip Center Height After THA

Other than femoral head dislocation height, soft tissue contracture, bony LLD, and pelvic malformation, the hip rotational center can also affect leg length. In cases with small and shallow acetabular, it is difficult to predict cup size and position of Crowe type IV DDH patients during the preoperative planning process<sup>25</sup>. In the study of Zhao *et al.*, 23 cases of Crowe type II and 18 cases of Crowe type III dysplasia hips were treated with THA while reconstructing the hip center at the anatomy level. At last they found the actual postoperative position of hip center for these patients was  $18.7 \pm 4.06$  mm above inter-teardrop line. To our knowledge, there are few researchers who have studied the postoperative hip center position of Crowe type IV DDH patients and no one has compared it with that of Crowe type I DDH patients. After surgery, we measured the vertical distance from cup center to teardrop line for every hip in two groups, and found that the height of hip rotational center of group A was significantly smaller than that of group B ( $14.20 \pm 5.02$  mm vs  $20.92 \pm 4.66$  mm,  $P < 0.001$ ). This result indicates that a more inferior hip rotational center could lead to a longer functional leg length. In our opinion, a more inferior hip rotational center is related to a severely small and shallow acetabular of Crowe type IV DDH patients, and, due to insufficient bone stock of anterior acetabular column, the acetabular cannot be fully reamed in order to preserve the bone of the anterior acetabular column as much as possible. On the other hand, due to it being difficult to predict the hip center position with HHD patients before THA, leg length balance must be done after reduction to correct leg length change caused by cup position.



### Clinical Improvement

In this study, HHS of Crowe type IV patients was improved from  $57.53 \pm 11.59$  to  $89.82 \pm 3.03$  ( $P < 0.01$ ), which is consistent with previous studies<sup>12,23</sup>. However, before THA, we found no significant difference of HHS, SF-12 PCS, or SF-12 MCS between groups A and B. We reason that this may be due to the fact that patients in group A were roughly 11 years younger than those in group B. Although patients in group A harbored much more severe dysplasia in the hips, most of the patients in group B had a longer disease course and developed secondary lesions such as osteoarthritis and femoral head necrosis. After surgery, we observed a significantly lower SF-12 MCS of group-A than that of group-B patients. We concluded that this was also related to the significant age difference. Compared to patients in group B, group A patients had a higher motor requirement while they simultaneously possessed longer recovery times.

### Limitations

There are several limitations to the scope of this study. First, the sample size is relatively small (17 hips for group A and 20 hips for group B). However, Crowe type IV/I DDH patients combined with other Crowe-type DDH hips were excluded. Second, we did not test intraobserver and the interobserver agreement during radiological measurements. However, these measurement methods are nonetheless in line with previous studies, and they have been verified as having strong reproducibility. Third, we did not gain full leg length radiographs post-surgery, therefore we could not study any effect of stem position to leg length further.

### Conclusion

After elaborate preoperative planning and leg length balancing during operation, THA combined with transverse subtrochanteric osteotomy is an effective method to achieve equal function in leg length.

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### Author Declarations

All authors listed meet the authorship criteria according to the latest guidelines of the International Committee of Medical Journal Editors. All authors are in agreement with the manuscript.

### Ethical approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the Institutional Review Board (IRB) of the First Hospital of Jilin University and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

### Informed consent

Informed consent was obtained from all individual participants included in the study.

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