Developmental dysplasia of the hip (DDH) is the leading cause of hip arthritis in young adults. Several nonarthroplasty treatments, including proximal femoral and periacetabular osteotomies, can be performed prior to the development of end-stage osteoarthritis (OA) in these patients. However, total hip arthroplasty (THA) remains the standard of care when end-stage OA results in significant pain and loss of function.

For patients with DDH, THA presents many challenges including young patient age, distorted anatomy, and documented high failure and revision rates. Clinical improvements such as high hip rotation center technique and bone graft have been widely used and have generated satisfactory long-term implant stability and lower limb function. Although patient satisfaction and orthopedic scores may demonstrate significant improvement, gait analysis can highlight small discrepancies in the joint angles and loading that are not within the normal range or signs of functional improvement in THA patients. Therefore, further quantified functional gait analysis can be beneficial in understanding the outcomes of THA in patients with DDH.

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Although many researchers have performed gait analysis on THA patients postoperatively, for patients with DDH, especially those with Crowe type II and III, the effects of leg-length discrepancy on the unaffected (unoperated on) side in unilateral THA patients and gait symmetry in bilateral THA patients remain unclear. The gait rebalance of the 2 sides for unilateral and bilateral THA patients probably would differ. The gait function of patients with DDH after THA and the controversies regarding the acetabular cup position also need further research.

This study evaluated gait function and joint kinematics in unilateral and bilateral THA patients with Crowe type II and III DDH. In addition, the effect of a high hip center on gait function was investigated. The study hypothesis was that the unilateral and bilateral groups would have functional differences in outcomes and that different levels of high cup position would affect the gait patterns.

**MATERIALS AND METHODS**

All patients undergoing THA performed by a senior arthroplasty surgeon at a single center who were qualified in accordance with the prespecified inclusion and exclusion criteria were invited to participate in the study. The inclusion criteria were cementless primary THA and a diagnosis of OA secondary to DDH. Patients with a diagnosis other than degenerative hip arthropathy, history of previous orthopedic surgery, polyarthritis, neurologic disorder known to affect gait, limp, inability to walk without a cane or a walker, and hip pain or discomfort, as well as patients who were not willing to comply with the study protocol were excluded from the study.

A total of 31 patients (6 men and 25 women) participated in the study and provided informed written consent. Mean patient age, height, and body weight were 56.3 (SD, 8.7) years, 157.1 (SD, 7.1) cm, and 58.7 (SD, 8.7) kg, respectively. Mean follow-up was 23.4 (SD, 6.3) months (range, 12-36 months). Sixteen patients (3 men and 13 women) underwent unilateral THA for unilateral OA secondary to DDH, and 15 patients (3 men and 12 women) underwent bilateral THA performed separately at an average interval of 7 weeks (range, 1-18 weeks).

Of the 46 dysplastic hips, 35 hips were classified as Crowe type II, and 11 hips were classified as Crowe type III. A posterolateral approach was used for all of the hip surgeries. A cementless acetabular component and femoral stem (DePuy, Warsaw, Indiana) with a ceramic-on-ceramic bearing were used in all of the THAs. One Crowe type III DDH patient in the unilateral group required bone grafting for coverage of the acetabular cup.

Similar distributions in cup size (P=.844), head size (P=.904), age (P=.534), height (P=.163), weight (P=.533), and follow-up (P=.717) in the unilateral and bilateral groups were observed. In the unilateral group (12 Crowe type II patients and 4 Crowe type III patients), 10 acetabular cups were positioned at the true acetabulum, and 6 acetabular cups were placed at a high position. In the bilateral group (23 Crowe type II patients and 7 Crowe type III patients), 22 acetabular cups were positioned at the true acetabulum, and 8 acetabular cups were placed at a high position. The intertrochanteric line on the postoperative anteroposterior pelvic radiographs was used as the reference, and the distance between the center of the femoral head and the intertrochanteric line was measured to quantify the level of the superior displacement of the cup.

Leg-length discrepancy after THA was defined as the difference in the perpendicular distance between the intertrochanteric tip of the lesser trochanter, which was measured in millimeters (Figure 1). After surgery, patients began to exercise daily under the doctor’s guidance until discharge from the hospital. At discharge, patients were instructed to continue the exercises. Patients also were encouraged to use a walker.
Gait analysis for patients who underwent THA occurred at least 1 year after surgery. In a gait laboratory, each patient walked at a self-selected pace on a 12-m walkway. Patients wore 28 retroreflective markers to track pelvis motions as well as both thighs, shanks, and feet (Figure 2). An initial standing static trial was performed using 10 additional markers placed over the ankle, femoral epicondyles, and greater trochanter to determine segment orientations. Three-dimensional trajectories of the markers were collected at 290 Hz using a 10-camera motion analysis system (Oqus 300; Qualisys, Gothenburg, Sweden). Ground reaction forces (GRFs) were recorded at 540 Hz by using 2 force plates (Bertec Corporation, Columbus, Ohio) that were incorporated into the walkway.

Patients performed 5 gait trials (the first 2 trials were used to adopt the testing procedures and were not included in the final results) and were instructed to walk as naturally as possible and to look straight ahead. In addition, 10 healthy participants (5 men and 5 women) served as a control group. Mean age, height, and body weight were 58.4 (SD, 6.3) years, 153.4 (SD, 6.8) cm, and 60.8 (SD, 10.2) kg, respectively, and were matched with the unilateral and bilateral groups.

Spatiotemporal parameters analyzed were gait velocity (S), single-limb stance (SLS) time, and double-limb stance (DLS) time. Sagittal (flexion/extension), frontal (adduction/abduction), and transverse (internal/external rotation) plane hip range of motion (ROM) were calculated using the custom PIPELINE command of a commercially available software program (Visual 3D; C-Motion Inc, Rockville, Maryland). For between-subject comparisons, the SLS and DLS times were normalized as a percentage of the gait cycle time. For the control group, each of the gait variables was calculated for each limb and then averaged across the limbs for each trial.

Statistical analyses were performed using SPSS version 19 software (SPSS Inc, Chicago, Illinois). Analysis of variance was used to detect differences among the 3 groups, and an independent t test was used to detect differences between the unilateral and bilateral groups. A paired t test was used to determine the differences between the 2 sides of participants. The level of significance was set at α=0.05. The study was approved by the institutional review board of West China Hospital, Sichuan University, and informed consent was obtained from each participant.

**RESULTS**

Gait parameters, particularly sagittal (flexion/extension) and frontal (adduction/abduction) hip joint ROM, in the unilateral and bilateral groups were significantly lower than those in the healthy control group. A significant influence of a high acetabular cup position on hip joint kinematic parameters was not found in the unilateral THA group but was observed in the bilateral THA group. There was a significant difference in sagittal hip ROM for the unilateral and bilateral THA groups.

No significant differences were detected in the spatiotemporal parameters among the control, unilateral, and bilateral groups (P>.05), except for gait velocity between the unilateral and bilateral THA groups (P=.048). Regarding hip joint kinematic parameters, mean sagittal and frontal hip ROM in the unilateral THA group (38.2° and 10.3°, respectively) and the bilateral THA group (34.2° and 9.8°, respectively) were significantly lower (P<.001) than in the control group (45.2° and 15.7°, respectively). However, no significant differences were observed in 3-plane hip ROM between the unilateral and bilateral THA groups (Table 1).

Regarding the unaffected (unoperated on) side of the unilateral THA group, SLS time and frontal hip ROM were significantly lower than in the control group (P=.013 and .011, respectively). No significant differences in SLS time and 2-plane hip ROM were noted between the unaffected (unoperated on) and affected (operated on) sides of the unilateral THA group (Table 2).

To further investigate whether significant differences existed within the unilateral THA group regarding spatiotemporal and hip joint kinematic parameters, the unilateral THA group was divided into 4 subgroups on the basis of high (H) or true (T) position of the acetabular cup and the unaffected (unoperated on) or affected (operated on) sides; however, no significant differences were found. Mean (SD) level of the cup superior displacement was 11.8 (1.9) mm (Table 3), and mean leg-length discrepancy of the high cup position subgroup was 7.1 (3.9) mm. The effects of the operated on (affected) side on the function of the unoperated on (unaffected) side and that of the high cup position on gait function were not significant (P>.05 for all conditions).

Similarly, the bilateral THA group was separated into 4 subgroups on the basis of both true position of the acetabular cups and the 2 sides. Mean (SD) level of high cup displacement was 21.3 (2.2) mm. Mean leg-length discrepancy of the high and true subgroups was 18.0 (2.3) mm. The spatiotemporal parameter values were similar among the subgroups. Regarding the SLS time and 3-plane hip ROM, no significant differences were observed be-
between the 2 sides in both true subgroups. However, significant differences in terms of the SLS time and the 3-plane hip ROM were found in the high and true subgroups (Table 4).

In addition, sagittal hip ROM improved significantly on the affected (operated on) side of the unilateral group compared with both true subgroups of the bilateral group (P=.024). No significant differences were found in frontal and transverse hip ROM.

**Discussion**

Abnormal gait in patients with unilateral DDH includes slower than normal walking speed, shorter steps, less anterior pelvic tilt, more hiking on the affected side, more rotation toward the unaffected side of the pelvis, and reduced hip sagittal motion but greater knee and ankle flexion.\(^{15}\) Reduced hip sagittal moments, and hip and knee abductor moments, together with decreased GRFs during the initial DLS, also were found in these patients.\(^{16,17}\) These compensations are protective mechanisms to diminish the loads and pain on the dysplastic hip.

Generally, the gait of patients with unilateral DDH is asymmetrical and less efficient than that of healthy controls.\(^{15}\) In the current study, patients with DDH who underwent unilateral THA demonstrated similar gait velocity, DLS time, and SLS time but significantly lower sagittal and frontal hip joint ROM on the affected (operated on) side than those of the healthy control group. The compensation mechanism of the unaffected (unoperated on) side in protecting the affected (operated on) side after unilateral THA remains because reduced SLS time and sagittal and frontal hip joint ROM were observed on the affected (unoperated on) side compared with those of the healthy control group. The compensation mechanism of the unaffected (unoperated on) side in protecting the affected (operated on) side after unilateral THA remains because reduced SLS time and sagittal and frontal hip joint ROM were observed on the affected (unoperated on) side compared with those of the healthy control group. Although the gait of patients undergoing unilateral THA was less efficient than that of the healthy control group, the main spatiotemporal and

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### Table 1

**Gait Cycle and Hip ROM for Control, Unilateral THA, and Bilateral THA Groups**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Control Group (n=10)</th>
<th>Unilateral THA Group (n=16)</th>
<th>Bilateral THA Group (n=15; 30 hips)</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gait velocity, m/s</td>
<td>1.2 (0.2)</td>
<td>1.1 (0.1)</td>
<td>0.9 (0.3)</td>
<td>.677</td>
</tr>
<tr>
<td>DLS, % gait cycle</td>
<td>24.2 (4.0)</td>
<td>20.1 (2.5)</td>
<td>24.7 (9.4)</td>
<td>.278</td>
</tr>
<tr>
<td>SLS, % gait cycle</td>
<td>62.2 (2.0)</td>
<td>60.6 (1.6)</td>
<td>62.2 (4.4)</td>
<td>.258</td>
</tr>
<tr>
<td>Hip ROM</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sagittal, flexion/extension</td>
<td>45.2° (2.6°)</td>
<td>38.2° (5.3°)</td>
<td>34.2° (5.3°)</td>
<td>.004*</td>
</tr>
<tr>
<td>Frontal, adduction/abduction</td>
<td>15.7° (3.3°)</td>
<td>10.3° (2.2°)</td>
<td>9.8° (2.9°)</td>
<td>&lt;.001*</td>
</tr>
<tr>
<td>Transverse, internal/external rotation</td>
<td>14.3° (3.7°)</td>
<td>13.6° (2.3°)</td>
<td>11.6° (3.4°)</td>
<td>.642</td>
</tr>
</tbody>
</table>

Abbreviations: DLS, double-limb stance; ROM, range of motion; SLS, single-limb stance; THA, total hip arthroplasty.

*Parameters SLS and sagittal, frontal, and transverse hip ROM are from the affected (operative) side of the unilateral THA group.

*Comparisons between control group and unilateral THA group.

*Comparisons between control group and bilateral THA group.

*Comparisons between unilateral THA group and bilateral THA group (using one-way analysis of variance).

*Significant difference (P<.05).

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### Table 2

**SLS and Hip ROM of Unaffected Side in the Unilateral THA Group**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean (SD) Unilateral THA Group (Unaffected and Nonoperative Side, n=16)</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLS, % gait cycle</td>
<td>60.2 (1.2)</td>
<td>.013&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>Hip ROM</td>
<td></td>
<td>.491</td>
</tr>
<tr>
<td>Sagittal, flexion/extension</td>
<td>40.7° (7.3°)</td>
<td>.118</td>
</tr>
<tr>
<td>Frontal, adduction/abduction</td>
<td>11.7° (2.6°)</td>
<td>.011&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>Transverse, internal/external rotation</td>
<td>14.4° (4.1°)</td>
<td>.953</td>
</tr>
</tbody>
</table>

Abbreviations: ROM, range of motion; SLS, single-limb stance; THA, total hip arthroplasty.

*Comparison between unaffected (nonoperative) side of the unilateral THA group and control group (using independent t tests).

*Comparison between unaffected (nonoperative) and affected (operative) side of the unilateral THA group (using paired t tests).

*Significant difference (P<.05).
kinematic parameters between the affected (operated on) and unaffected (unoperated on) sides were symmetrical. Therefore, this functional symmetry in unilateral THA patients can contribute in balancing the asymmetrical loading between the 2 sides and can decrease the contralateral OA risk following unilateral THA.  

Most studies on gait function after THA include a majority of patients with unilateral disability. One of the few gait analyses comparing gait parameters between unilateral and bilateral THA patients concluded that unilateral replacement significantly enhanced gait function.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean (SD) High With LLD</th>
<th>Mean (SD) True Without LLD</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unaffected(a)</td>
<td>Affected(b)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(n=6)</td>
<td>(n=6)</td>
<td></td>
</tr>
<tr>
<td>Gait velocity, m/s</td>
<td>1.1 (0.1)</td>
<td>1.1 (0.1)</td>
<td>.357</td>
</tr>
<tr>
<td>DLS, % gait cycle</td>
<td>20.6 (1.8)</td>
<td>20.6 (3.4)</td>
<td>1.000</td>
</tr>
<tr>
<td>SLS, % gait cycle</td>
<td>60.4 (1.0)</td>
<td>60.6 (1.4)</td>
<td>.516/883</td>
</tr>
<tr>
<td>Hip ROM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sagittal, flexion/extension</td>
<td>40.9° (7.8°)</td>
<td>37.2° (3.5°)</td>
<td>.940/.591</td>
</tr>
<tr>
<td>Frontal, adduction/abduction</td>
<td>12.1° (2.1°)</td>
<td>10.2° (1.3°)</td>
<td>.641/.904</td>
</tr>
<tr>
<td>Transverse, internal/external rotation</td>
<td>14.9° (5.1°)</td>
<td>12.7° (2.9°)</td>
<td>.748/281</td>
</tr>
</tbody>
</table>

**Table 3**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean (SD) Both True (Without LLD)</th>
<th>Mean (SD) High and True (With LLD)</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Left (n=7)</td>
<td>Right (n=7)</td>
<td></td>
</tr>
<tr>
<td>Gait velocity, m/s</td>
<td>0.8 (0.3)</td>
<td>1.0 (0.1)</td>
<td>.378</td>
</tr>
<tr>
<td>DLS, % gait cycle</td>
<td>28.5 (10.6)</td>
<td>19.1 (5.0)</td>
<td>.338</td>
</tr>
<tr>
<td>SLS, % gait cycle</td>
<td>63.1 (4.3)</td>
<td>64.73 (6.3)</td>
<td>.149</td>
</tr>
<tr>
<td>Hip ROM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sagittal, flexion/extension</td>
<td>33.1° (2.8°)</td>
<td>29.9° (6.4°)</td>
<td>.320</td>
</tr>
<tr>
<td>Frontal, adduction/abduction</td>
<td>10.3° (3.8°)</td>
<td>9.5° (4.4°)</td>
<td>.543</td>
</tr>
<tr>
<td>Transverse, internal/external rotation</td>
<td>11.0° (1.9°)</td>
<td>12.3° (5.4°)</td>
<td>.776</td>
</tr>
</tbody>
</table>

**Table 4**

Abbreviations: DLS, double-limb stance; LLD, leg-length discrepancy; ROM, range of motion; SLS, single-limb stance; THA, total hip arthroplasty.

*Unaffected (nonoperative) side.
*Affected (operative) side.
*Comparisons between high and true cup position subgroups (using independent t tests).
*Comparisons between unaffected and affected sides within high cup position subgroup (using paired t test).
*Comparisons between unaffected and affected sides within true cup position subgroup (using paired t test).
compared with bilateral procedures. The findings of the current study showed that despite the absence of significant differences in most gait parameters between the unilateral and bilateral THA groups, the values of spatiotemporal and kinematic parameters were more positive in the unilateral THA group than in the bilateral THA group. When the bilateral THA subgroups were considered, the findings indicated a better gait function on the affected (operated on) side in the unilateral THA group than in the bilateral THA group without leg-length discrepancy; this finding was in accord with previous reports. The better gait function in the unilateral THA group may result from the compensation mechanism of the unaffected (unoperated on) side in protecting the affected (operated on) side; however, this was not observed in the bilateral THA group. Exercises in strengthening the hip flexors, hip abductors, and knee extensors probably helped to further improve the gait patterns.

The high hip center technique has been advocated as a compromise for use in dysplastic hips and complex acetabular revisions. Clinical studies reported variable outcomes resulting from the high hip center technique. Provision of a guide is difficult in the process of acetabular reconstruction for a certain type of hip dysplasia. Controversy regarding the acetabular cup position in THA for patients with a dysplastic hip still exists. Most importantly, whether high acetabular cup position restores the normal hip biomechanics and ensures the symmetrical function for both hips remains unclear.

In the current study, the level of superior displacement of the cup was quantified, and subgroups in both the unilateral and bilateral THA groups were generated. Given a mean level of 11.8 (SD, 1.9) mm in the cup superior displacement with a mean leg-length discrepancy of 7.1 (SD, 3.9) mm, the findings suggested that the effect of high cup position on the symmetrical gait function for the affected (operated on) and unaffected (unoperated on) hips in the unilateral THA group was not significant. However, in the bilateral THA group, asymmetrical gait function for both hips was observed regarding the sagittal hip ROM at a mean level of 21.3 (SD, 2.2) mm for the cup superior displacement with a mean leg-length discrepancy of 18.0 (SD, 2.3) mm.

Consequently, high cup superior displacement will increase the significance of leg-length discrepancy. Keršić et al. reported that a leg-length discrepancy less than 7 mm was unperceived by patients after THA and that the influence of leg-length discrepancy less than 10 mm on the overall clinical outcome was detectable but not considerable. In the current study, the mean leg-length discrepancy in patients after unilateral THA was 7.1 (SD, 3.9) mm, and the function difference between the affected (operated on) and unaffected (unoperated on) hips was not significant. Therefore, the variation in the effects of high cup position on gait function in the unilateral and bilateral THA groups probably was ascribed to the different levels of cup superior displacement. According to Antoniades and Pellegrini, reconstructing the acetabulum within a 20-mm level of cup superior displacement may be the ideal choice to restore the normal hip biomechanics and ensure symmetrical function of both hips.

There were some limitations of the current study. First, the sample size was relatively small. More THA patients with DDH should be included to improve the power of the statistics and further investigate the effect of high cup position on gait. Second, the follow-up time was relatively short. Future studies in tracking THA patients with DDH can help to evaluate their gait patterns and optimize the exercise programs.

**CONCLUSION**

Although symmetrical gait between affected (operated on) and unaffected (unoperated on) sides in patients with DDH after unilateral THA was observed after mean follow-up of 23.4 months, both unilateral and bilateral THA patients still showed less efficient gait than that of healthy participants. Based on this study and related research about the impact of leg-length discrepancy on gait function, cup superior displacement within 12 mm in patients with DDH after unilateral THA contributes to the restoration of normal hip biomechanics.

**REFERENCES**

9. Kranzl A, Pospischil M, Simonotti L, Knahr K. P056 gait analysis of patients with a mini-


