MSM

ANIMAL STUDY

e-ISSN 1643-3750
© Med Sci Monit, 2026; 32: e952747
DOI: 10.12659/MSM.952747

Received: 2026.01.09
Accepted: 2026.05.08
Available online: 2026.06.15
Published: 2026.XX.XX

Evaluation of Changes in Hip Morphology in a Rabbit Model of Patellar Dislocation via Computed Tomography Imaging

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Study Design A
Data Collection B
Statistical Analysis C
Data Interpretation D
Manuscript Preparation E
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Financial support: This study was supported by the Medical Science Research Project of Hebei (Grant No. 20240032)
Conflict of interest: None declared

Background: Although early patellar dislocation induces morphological changes in the patellofemoral joint, its potential influence on hip morphology during growth remains unclear. This study evaluated changes in hip morphology via computed tomography (CT) imaging in a rabbit model of patellar dislocation.

Material/Methods: Thirty female New Zealand White rabbits (2 months old) were included. The left hindlimbs of rabbits (n=28 after 2 postoperative deaths) underwent patellar dislocation surgery and comprised the study group. Contralateral right hindlimbs (n=28), which underwent no surgical procedure, served as the control group. Anteroposterior pelvic radiographs and CT scans were obtained immediately after surgery and 4 months later. Central edge angle, acetabular abduction angle, acetabular version, pubic relative length, ischiac relative distance (IRD), and femoral version were measured and analyzed.

Results: No significant differences were observed immediately after surgery. Four months later, acetabular version (study group: 24.83±5.50°; control group: 16.14±5.15°; $P<0.001$), IRD (study group: 1.85±0.08 mm; control group: 1.77±0.11 mm; $P=0.002$), and femoral version (study group: -3.11±4.17°; control group: 4.15±5.02°; $P<0.001$) significantly differed between groups. Acetabular version showed a negative correlation with femoral version (r=-0.813, $P<0.001$) and a positive correlation with IRD (r=0.563, $P<0.001$).

Conclusions: Early patellar dislocation in growing rabbits led to significant alterations in acetabular version, femoral version, and IRD, suggesting that patellar dislocation can influence hip development during growth.

Keywords: **acetabulum • femur • joint instability • orthopedics • patellar dislocation • radiography**

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Introduction

Patients with developmental dysplasia of the hip often exhibit increased patellar tilt and shallow trochlear grooves, which are features associated with patellar dislocation [1-3]. In contrast, patients with recurrent patellar dislocation frequently demonstrate acetabular characteristics of developmental dysplasia of the hip [4,5]. Intriguingly, both populations commonly exhibit increased femoral version [6-9]. For example, Fan et al [5] conducted a morphological analysis of the hip joints in patients with recurrent patellar dislocation. They found significantly increased acetabular version and reduced acetabular coverage compared with controls, providing clinical evidence for a morphological relationship between the hip and knee. Taken together, these findings suggest that abnormal acetabular version, and potentially broader hip morphological abnormalities, may be associated with patellar dislocation.

The biomechanical interdependence of the hip and knee joints during growth is increasingly recognized. Szybist et al. [10] identified increased femoral internal rotation and weak hip external rotators as key risk factors for patellofemoral pain, further supporting the proximal-distal relationship. Conversely, distal joint pathology may influence proximal function; Xie et al [11] found that patients with patellofemoral pain syndrome exhibited weaker hip external rotation and abduction strength than controls, suggesting that knee disorders can alter muscle control at the hip. At the developmental level, Yadav et al [12] used finite element models to demonstrate that muscle forces directly influence proximal femoral growth, offering a potential mechanism through which altered loading from the knee could affect hip morphology during development. Given this bidirectional relationship and the anatomical continuity provided by the femur, it is plausible that early patellar dislocation influences hip development through altered biomechanical loading across the lower extremity. However, direct experimental evidence linking patellar instability to subsequent hip morphological changes during growth has not been documented; this lack of evidence served as the rationale for the present animal study.

Rabbits are well suited for this study because they mature rapidly (by 6-7 months) [13], and their knee anatomy resembles that of humans [14,15]. The rabbit model of patellar dislocation involves surgical induction via medial retinacular incision and lateral retinacular overlap suturing; it has been validated in previous studies. Previous rabbit models have successfully demonstrated that patellar dislocation results in trochlear dysplasia and an increased tibial tuberosity-trochlear groove distance [16-20], confirming the validity of the model. Such factors make rabbits a logical choice for investigating whether patellar dislocation also affects hip development.

Although clinical observations suggest a relationship between patellar dislocation and hip morphology [4,5], and femoral version displays known correlations with knee and hip parameters [6-9], no animal study has directly investigated whether early patellar dislocation can influence hip development during growth. Therefore, this study aimed to evaluate changes in hip morphology via computed tomography (CT) imaging in a rabbit model of patellar dislocation. The null hypothesis was that hip joint morphology would not significantly change after early patellar dislocation.

Material and Methods

Ethical Approval

This study was approved by the Institutional Animal Care and Use Committee (IACUC) of Hebei Medical University Third Hospital (Approval No. Z2024-023-01; approved on May 6, 2024). All procedures were performed in accordance with the Guide for the Care and Use of Laboratory Animals.

Study Design and Setting

Thirty female New Zealand rabbits (2 months old; weight: 350-450 g) were obtained from the Animal Center of Tong Hui Laboratory and included in the study. The left hindlimbs, which underwent surgery to induce lateral patellar dislocation, were defined as the study group. The contralateral hindlimbs served as the control group and underwent no surgical procedure. Rabbits were housed under standard conditions (temperature: 22 ± 2 °C; humidity: 55% ± 5%; unrestricted access to food and water; 12-hour light-dark cycle).

Surgical Procedures

The surgical procedure for patellar dislocation was based on previous studies [16-20]. Rabbits were anesthetized before surgery by intravenous injection of pentobarbital sodium solution (35 mg/kg; Sigma-Aldrich, St. Louis, MO, USA) via the marginal ear vein. In the study group, the left knee was shaved and disinfected. A 3-cm longitudinal incision was made, and soft tissues were carefully dissected to expose the medial retinaculum. The medial retinaculum was incised; the lateral retinaculum was overlapped and sutured in a shortened position. The knee was then passively flexed and extended to confirm lateral displacement of the patella from the femoral trochlear groove. The incision was closed in layers, and the wound was covered with gauze. Postoperative pain was managed with oral ibuprofen suspension (Motrin®; Johnson & Johnson Pharmaceutical Ltd., Shanghai, China) at a dose of 15 mg/kg body weight every 12 hours for 3 days. This regimen was based on established protocols in rabbit models [21,22]. Cefuroxime

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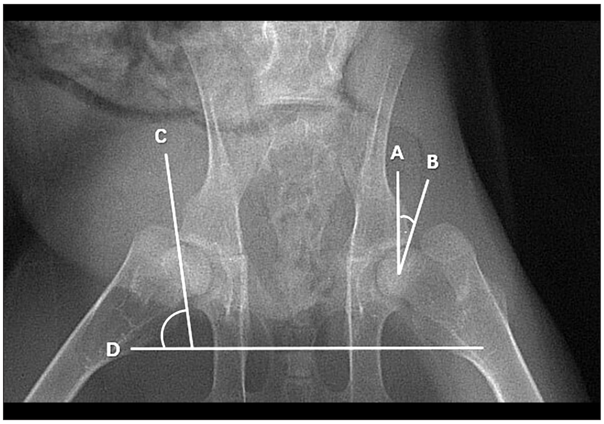

Figure 1. Schematic diagram of central edge angle and acetabular abduction angle. This figure illustrates the radiographic measurement method used for acetabular coverage assessment. Lines: Line A, vertical line passing through the center of the femoral head; Line B, line connecting the femoral head center and the superolateral acetabular rim; Line C, line connecting the lateral acetabular margins; Line D, horizontal reference line. Measurements: Central edge angle, angle between lines A and B; Acetabular abduction angle: angle between lines C and D.

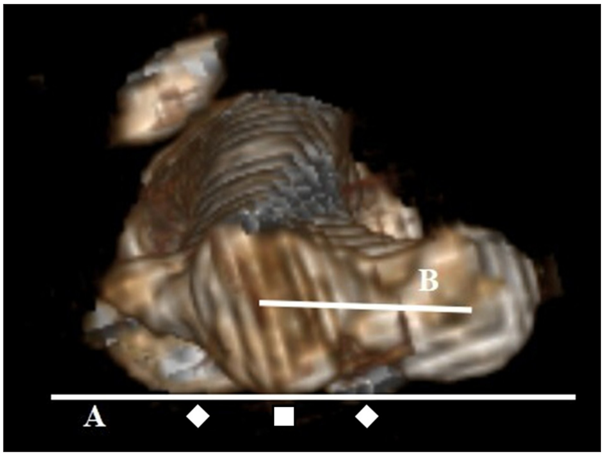

Figure 2. Schematic diagram of femoral version. This figure demonstrates the 3-dimensional computed tomography measurement method for femoral version. Lines: Line A, line connecting the greater trochanter (□) and the medial and lateral posterior femoral condyles (◇); Line B, line connecting the center of the femoral head and the midpoint of the narrowest portion of the femoral neck. Measurement: Femoral version, angle between lines A and B. Positive values indicate anteversion, whereas negative values indicate retroversion.

(Esseti Pharmaceutical Co., Ltd., Nanjing, China) was administered intravenously at a dose of 18.75 mg/kg every 8 hours for 24 hours as infection prophylaxis [23].

Imaging Evaluation

Immediately after completion of surgery, while rabbits remained under anesthesia, anteroposterior (AP) pelvic radiographs (Carestream Health, Rochester, NY, USA) and CT scans (SOMATOM Sensation 16; Siemens Medical Solutions, Erlangen, Germany; voltage: 120 kV; current: 200 mA) were obtained with the rabbits in a supine position. Four months after surgery, rabbits were euthanized by intravenous overdose administration of pentobarbital sodium solution (110 mg/kg; Sigma-Aldrich) via the marginal ear vein. AP radiographs and CT scans were then repeated with the rabbits in a supine position. By this time, the rabbits had reached skeletal maturity [24]. The scanning area extended from the most proximal aspect of the pelvis to the most distal aspect of the femur. Slice thickness was set at 1 mm.

Central edge angle (CEA; angle between Line A and Line B) and acetabular abduction angle (AAD; angle between Line C and Line D) were measured on AP pelvic radiographs via standard techniques in RadiAnt DICOM software (Medixant Ltd., Poznan, Poland) (**Figure 1**) [5,25]. Line A was a vertical line passing through the center of the femoral head. Line B connected the femoral head center and superolateral acetabular rim. Line C connected the lateral acetabular margins, and Line D served as a horizontal reference line.

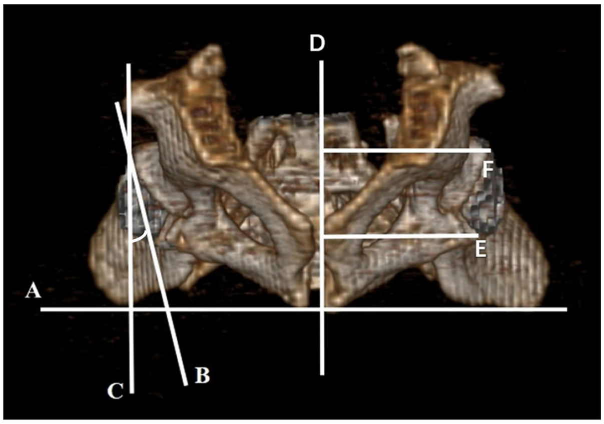

Figure 3. Schematic diagram of acetabular version, pubic relative length, and ischiac relative distance. This figure illustrates the 3-dimensional computed tomography measurement method for acetabular morphology from an inferior view. Lines: Line A, horizontal line connecting the bilateral anterior superior iliac spines and anterior pubic symphysis; Line B, line connecting the medial anterior and lateral posterior acetabular margins; Line C, line perpendicular to line A; Line D, line passing through the most medial margin of the pubis and perpendicular to line A; Line E, vertical line extending from the medial anterior acetabular margin to line D; Line F, vertical line extending from the lateral posterior acetabular margin to line D. Measurements: Acetabular version, angle between lines B and C; Pubic relative length, length of line E; Ischiac relative distance, length of line F.

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Given that 2-dimensional methods for measuring femoral and acetabular version have several limitations and inaccuracies, a 3-dimensional (3D) strategy described in previous studies was used, with an accuracy of 0.01° [26-30]. RadiAnt DICOM software (Medixant Ltd.) was used for 3D reconstruction and measurements.

To measure femoral version, the femur was reconstructed and positioned according to a standardized method. The lowest point of the greater trochanter was aligned with the midpoint between the medial and lateral femoral condyles [26-28]. Line A connected these 3 points (**Figure 2**). Line B connected the center of the femoral head and midpoint of the narrowest portion of the femoral neck. Femoral version was defined as the angle between Line A and Line B.

To measure acetabular version, the pelvis was subjected to 3D reconstruction and viewed from an inferior perspective, in accordance with a previously described method [30]. The pelvis was rotated and adjusted until both anterior superior iliac spines and the anterior pubic symphysis were aligned on the same horizontal Line A (**Figure 3**). The most medial point of the anterior acetabular margin and most lateral point of the posterior acetabular margin were connected by Line B. Acetabular version was defined as the angle between Line B and Line C, which was perpendicular to Line A. Line D passed through the most medial margin of the pubis and was perpendicular to Line A. Line E, drawn perpendicular to Line D, extended from the most medial point of the anterior acetabular margin. The length of Line E represented pubic relative length (PRL). Line F, also drawn perpendicular to Line D, extended from the most lateral point of the posterior acetabular margin. The length of Line F represented ischiac relative distance (IRD) [31].

Statistical Analysis

Results are expressed as mean ± standard deviation and were analyzed using SPSS version 21.0 (IBM Corp., Armonk, NY, USA). Levene's test and the Kolmogorov-Smirnov test were used to assess homogeneity of variance and normality of the data, respectively. The Mann-Whitney U test was used to assess non-normally distributed data. Paired t-tests were used to compare quantitative variables between the study and control groups. For comparisons performed immediately after surgery, *P*-values < 0.05 were considered statistically significant. For comparisons performed 4 months after surgery, Bonferroni correction was applied to adjust for multiple comparisons. Given the 6 primary outcome measurements, the significance threshold was adjusted to $P < 0.0083$ (0.05/6); only *P*-values below this threshold were considered statistically significant. Effect sizes (Cohen's d) were also calculated. Correlations between acetabular version and femoral version, as well as IRD, were assessed using Pearson's correlation coefficient.

To determine intra-observer and inter-observer reliability, femoral version and acetabular version measurements from the control group immediately after surgery were selected and evaluated using the intraclass correlation coefficient (ICC). ICC values > 0.75 were considered excellent, values < 0.40 poor, and values between 0.40 and 0.75 fair to good [32]. Intra-observer ICC values ranged from 0.899 to 0.976 for femoral version and from 0.820 to 0.905 for acetabular version. Inter-observer ICC values ranged from 0.864 to 0.967 for femoral version and from 0.642 to 0.906 for acetabular version.

Based on a clinically meaningful difference of 5° in femoral version, a standard deviation of 6° (derived from our previous work and the study by Wilkinson [33]), a 2-sided α of 0.05, and 80% power, a minimum sample size of 14 rabbits was required. Thus, the final sample size of 28 rabbits provided adequate statistical power for all comparisons.

Results

Measurements Immediately After Surgery

Two rabbits died after surgery because of infection, resulting in a final sample size of 28 animals for analysis. The CEA, AAD, acetabular version, PRL, IRD, and femoral version did not significantly differ between groups immediately after surgery (**Figure 4, Table 1**).

Measurements 4 Months After Surgery

When the rabbits reached skeletal maturity (4 months postoperatively), acetabular version (study group: 24.83 ± 5.50°; control group: 16.14 ± 5.15°; mean difference: 8.69°; 95% CI: 6.40° to 10.98°; $P < 0.001$), IRD (study group: 1.85 ± 0.08 mm; control group: 1.77 ± 0.11 mm; mean difference: 0.09 mm; 95% CI: 0.04-0.13 mm; $P = 0.002$), and femoral version (study group: -3.11 ± 4.17°; control group: 4.15 ± 5.02°; mean difference: -7.26°; 95% CI: -9.51° to -5.02°; $P < 0.001$) significantly differed between groups. The remaining indices showed no significant differences between groups (**Figure 5, Table 2**). Effect sizes (Cohen's d) were 1.47 for acetabular version, 1.25 for femoral version, and 0.66 for IRD, indicating clinically meaningful differences.

Correlation Analysis

Acetabular version was correlated with femoral version ($r = -0.813$, $P < 0.001$; **Figure 6**) and IRD ($r = 0.563$, $P < 0.001$; **Figure 7**) at 4 months after surgery.

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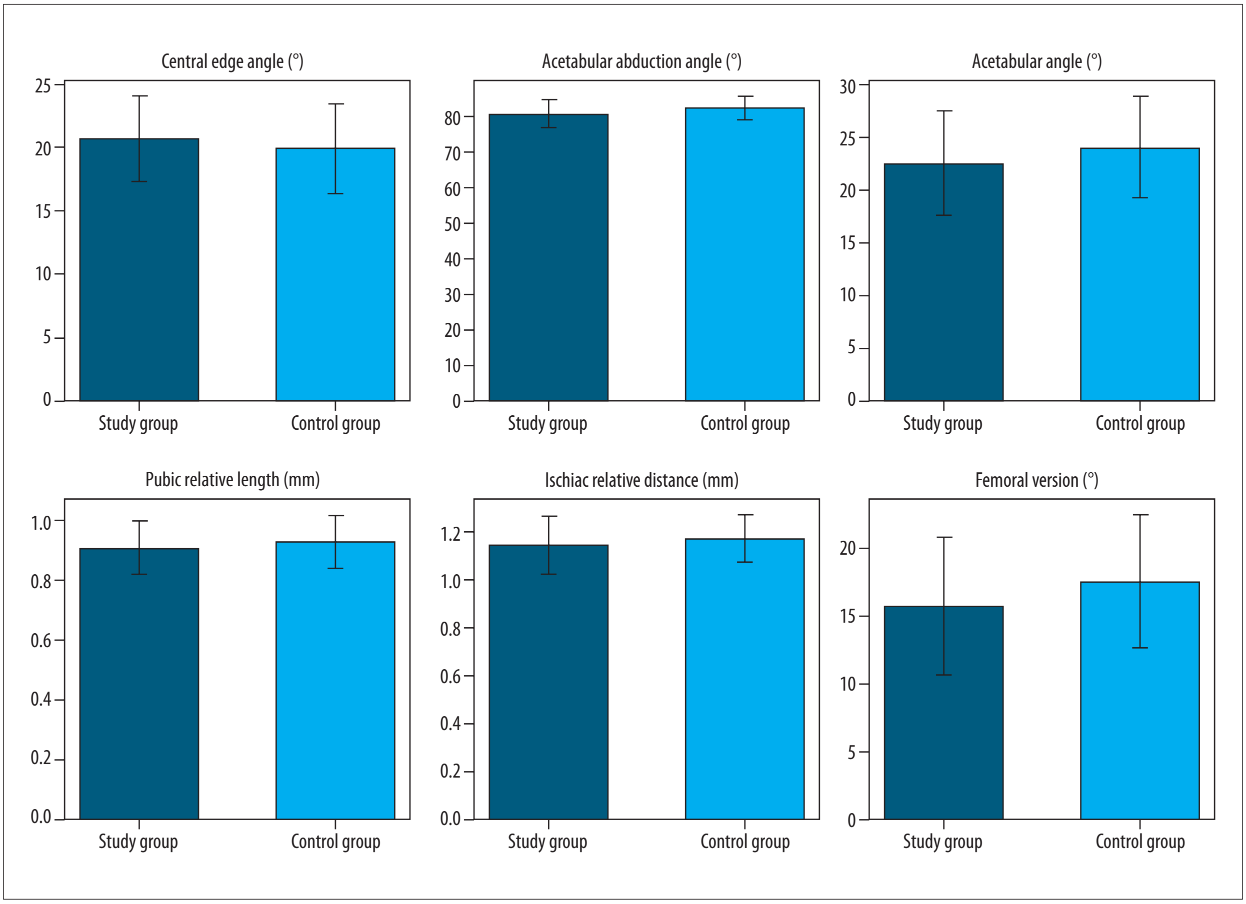

Figure 4. Measurements immediately after surgery. Bar graphs comparing all measured parameters between the study and control groups immediately after surgery. No significant differences were observed for any parameter (all *P*>0.05). Error bars represent standard deviations.

Table 1. Measurements immediately after surgery showing no significant differences between study and control groups.

Measurement	Study group	Control group	Mean difference (95% CI)	*P* value
CEA (°)	20.68±3.36	19.88±3.54	0.81 (-0.84 to 2.45)	0.33
AAD (°)	80.76±3.97	82.50±3.21	-1.73 (-3.75 to 0.28)	0.09
Acetabular version (°)	22.46±4.92	23.99±4.80	-1.53 (-4.01 to 0.95)	0.22
PRL (mm)	0.91±0.09	0.93±0.09	-0.01 (-0.06 to 0.03)	0.56
IRD (mm)	1.14±0.12	1.17±0.10	-0.03 (-0.07 to 0.02)	0.25
Femoral version (°)	15.76±5.06	17.63±4.93	-1.87 (-4.03 to 0.28)	0.09

Significance level: *P*<0.05. Abbreviations: AAD, acetabular abduction angle; CEA, central edge angle; CI, confidence interval; IRD, ischiac relative distance; PRL, pubic relative length.

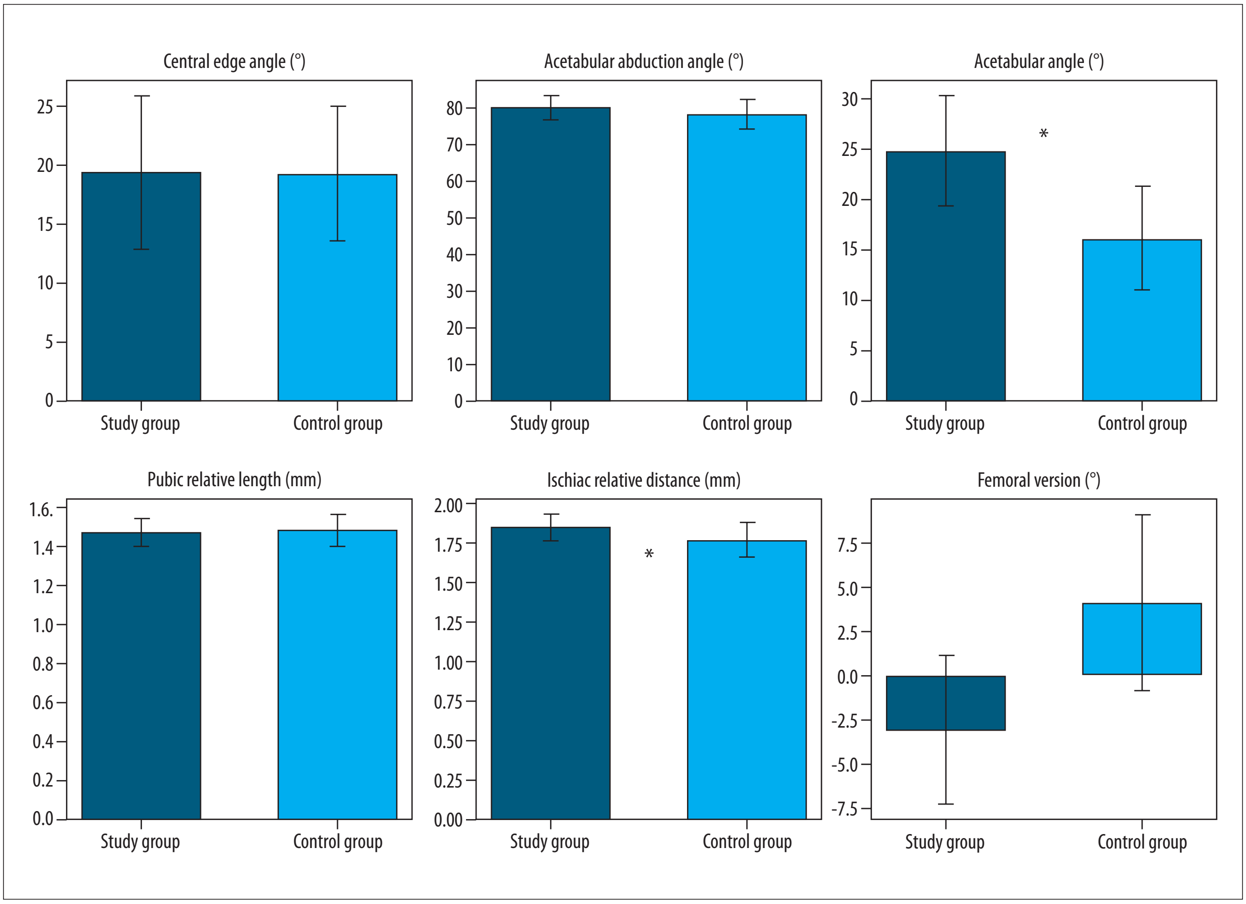

Figure 5. Measurements 4 months after surgery. Bar graphs comparing all measured parameters between the study and control groups 4 months after surgery. Asterisks (*) indicate statistically significant differences after Bonferroni correction (adjusted $P<0.0083$). Significant differences were observed for acetabular version, ischiac relative distance, and femoral version. Error bars represent standard deviations.

Table 2. Measurements 4 months after surgery showing significant differences in acetabular version, IRD, and femoral version between study and control groups.

Measurement	Study group	Control group	Mean difference (95% CI)	*P* value
CEA (°)	19.35±6.47	19.28±5.68	0.07 (-1.96 to 2.10)	0.95
AAD (°)	80.22±3.29	78.47±3.99	1.75 (-0.10 to 3.60)	0.06
Acetabular version (°)	24.83±5.50	16.14±5.15	8.69 (6.40 to 10.98)	<0.001
PRL (mm)	1.47±0.07	1.48±0.08	-0.01 (-0.05 to 0.03)	0.69
IRD (mm)	1.85±0.08	1.77±0.11	0.09 (0.04 to 0.13)	0.002
Femoral version (°)	-3.11±4.17	4.15±5.02	-7.26 (-9.51 to -5.02)	<0.001

Statistical significance was determined after Bonferroni correction for multiple comparisons (adjusted significance threshold: $P<0.0083$). Effect sizes (Cohen's d) for significant findings were: acetabular version (d=1.47), femoral version (d=1.25), and IRD (d=0.66). Abbreviations: AAD, acetabular abduction angle; CEA, central edge angle; CI, confidence interval; IRD, ischiac relative distance; PRL, pubic relative length.

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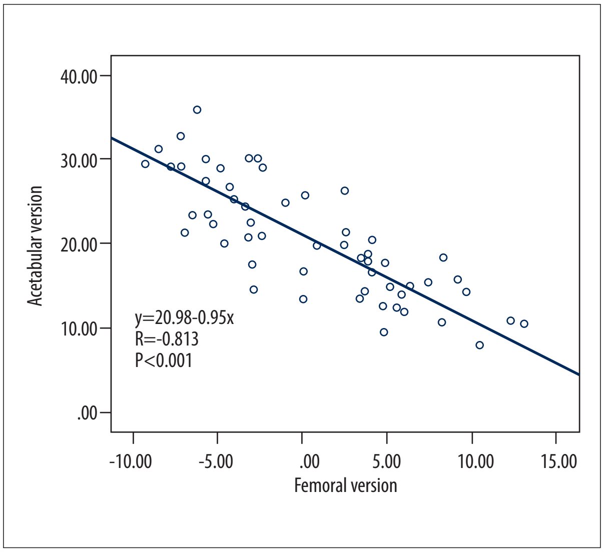

Figure 6. Negative correlation between acetabular version and femoral version. Scatter plot showing the correlation between acetabular version and femoral version 4 months after surgery (r = -0.813, *P* < 0.001). Each point represents 1 animal.

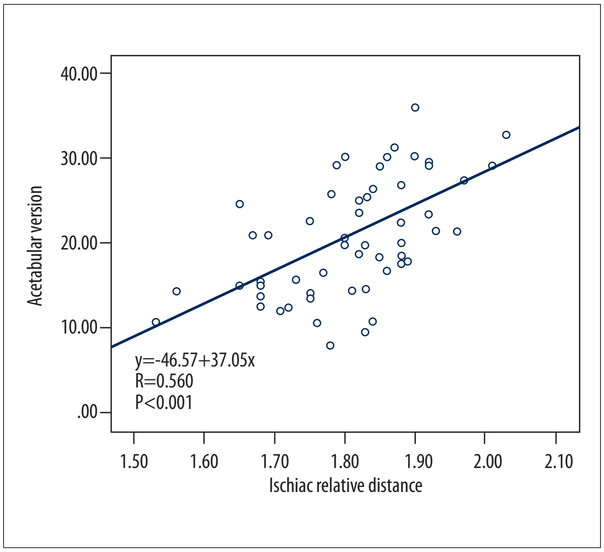

Figure 7. Positive correlation between acetabular version and ischiac relative distance. Scatter plot showing the correlation between acetabular version and ischiac relative distance 4 months after surgery (r = 0.563, *P* < 0.001). Each point represents 1 animal.

Discussion

This study showed that early patellar dislocation in growing rabbits resulted in significant morphological changes in the hip joint, including increased acetabular version, femoral retroversion, and increased IRD. Our findings extend the work of previous investigators who examined the effects of patellar malposition on knee joint development. Kaymaz et al [19] revealed that patellar malposition in growing rabbits leads to abnormal development of the femoral trochlear groove, with substantial alterations in trochlear morphology. Wang et al [17] demonstrated that early reduction of patellar subluxation could restore normal trochlear groove development, suggesting a window of developmental plasticity. Although these previous studies focused on changes in the knee joint, the present work is the first animal study to demonstrate that the effects of patellar dislocation extend proximally and influence hip morphology. Importantly, both humans and rabbits undergo developmental changes in version parameters during growth [33-38]. For example, in humans, femoral anteversion decreases from 30° to 40° at birth to 10° to 15° at skeletal maturity [36-38]. Similarly, femoral anteversion in rabbits decreases during growth and becomes negative (retroversion) at skeletal maturity [33].

In the present study, acetabular version in the study group was significantly greater 4 months after dislocation surgery. However, the CEA and AAD did not significantly differ between groups. To further explore the difference in acetabular version, the PRL and IRD were measured. The IRD was significantly greater in the study group, whereas the PRL showed no significant difference. These findings suggest excessive growth of the posterior region of the acetabulum after patellar dislocation in rabbits. In the study by Cho et al [39], the increase in acetabular version during growth was attributed to development of the secondary ossification center in the posterior region of the acetabulum, highlighting the importance of this area in acetabular remodeling. To further investigate this phenomenon, femoral version was measured, and its correlation with acetabular version was analyzed. The results showed that less femoral anteversion (or greater femoral retroversion) was associated with greater acetabular version. A significant correlation between acetabular version and femoral version was also observed after rabbits reached skeletal maturity. In a cadaveric study [40], subtrochanteric osteotomy was performed to retrovert the proximal femur by 10°. The cadaveric hips, positioned at 90° of flexion—a posture similar to the physiological state of rabbit hips—were tested under load. The location of peak joint pressure shifted posteriorly within the acetabulum. Combined with Wolff's law, these findings suggest that increased femoral retroversion after early patellar dislocation can shift loading posteriorly, leading to IRD overgrowth and increased acetabular version.

Morphological changes in the hip observed after early patellar dislocation may involve complex biomechanical adaptations. Patellar dislocation likely alters load transmission through the femur. Ozawa et al [41] demonstrated that reduced weight-bearing during growth in rats was associated with lateral patellar dislocation, suggesting that developing joints are highly sensitive to mechanical stimuli. Additionally, muscle function may be

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affected. Wu et al [42] reported electrophysiological and pathological abnormalities in the vastus medialis and vastus lateralis after patellar dislocation in rabbits, which could influence dynamic forces acting on the proximal femur. Compensatory gait changes may also occur. Recent clinical evidence has demonstrated that individuals with patellofemoral instability adopt quadriceps avoidance gait patterns characterized by reduced knee flexion moments and decreased quadriceps forces, thus altering joint loading distribution throughout the lower extremity [43]. Taken together, these factors may collectively contribute to adaptive remodeling of femoral version and acetabular morphology, providing a plausible—although speculative—link between early patellar dislocation and subsequent hip development. Further studies incorporating gait analysis and assessment of muscle function are needed to validate these potential mechanisms.

Version of the femur and acetabulum is closely related to the stability, function, and pathology of the knee and hip joints. Conditions such as femoroacetabular impingement, femoral fractures, hip dysplasia, patellar dislocation, Legg-Calvé-Perthes disease, and anterior cruciate ligament injury are associated with abnormal femoral or acetabular version [44-48]. In some cases, hip and knee joints should be considered together. For example, Fithian et al [49] found that patients with hip dysplasia had smaller femoral condyles, larger sulcus angles, shallower trochlear grooves, and greater patellar tilt relative to individuals with normal hips. DeVries et al [50] showed that infants with developmental dysplasia of the hip were 2.4 times more likely to have knees with trochlear dysplasia. Rajakulasingam et al [51] reported that patients with trochlear dysplasia had significantly increased anterior acetabular sector angles. In the present study, acetabular and femoral version significantly changed after early patellar dislocation in rabbits. These findings suggest that abnormalities in either the knee or hip joint can influence development of the other during growth. This relationship may be attributable to the anatomical continuity of the femur, where the proximal femur contributes to the hip joint and the distal femur contributes to the knee joint. The 2 joints may influence each other via mechanical transmission along the femur, particularly through alterations in femoral version.

This study has some limitations. First, use of the contralateral limb as a control may have introduced compensatory or systemic bias. Postsurgical gait alterations or systemic inflammatory responses could potentially affect the unoperated limb. Although preoperative measurements confirmed bilateral symmetry (**Table 1**), the inclusion of a separate sham-operated control group would have provided a more rigorous comparison. Second, rabbits and humans differ in key anatomical and developmental characteristics. Our model surgically induced patellar dislocation in previously stable knees; human patellar instability often involves underlying predisposing factors, such as trochlear dysplasia or soft tissue laxity [1-3]. Given these differences, our findings should be interpreted as hypothesis-generating observations in an animal model, rather than direct evidence for clinical practice. Third, this was an observational study. Thus, the mechanistic interpretations proposed above remain speculative because the study was not designed to directly assess biomechanical or molecular pathways. Moreover, we did not include gait analysis or muscle function assessment, which may provide important insights regarding mechanisms that underlie the observed morphological changes. Further investigations incorporating gait analysis, muscle force measurements, and molecular markers of bone remodeling are needed to clarify the precise mechanisms involved.

Conclusions

Early patellar dislocation in growing rabbits leads to significant alterations in acetabular version, femoral version, and IRD. These findings suggest that patellar dislocation can influence hip joint development during growth, highlighting the importance of considering hip morphology in patients with patellar dislocation.

Ethics Approval

Approval was obtained from the Animal Ethics Committee of Hebei Medical University Third Hospital before study initiation (Ethics No. Z2024-023-1).

Declaration of Figures' Authenticity

All figures submitted have been created by the authors who confirm that the images are original with no duplication and have not been previously published in whole or in part.

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