SHORT THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY (PHD)

Clinical and mechanical evaluation of roof step cut technique for hip dysplasia cases

by Lei Zhang

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The Examination takes place at University of Debrecen, Faculty of Medicine, Department of Orthopedics and Traumatology, Laboratory of Biomechanics, on December 3rd 2025, at 11:00.

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The **PhD defence** takes place at the Lecture Hall of Department of Internal Medicine, Building A, University of Debrecen, on December 3rd 2025, at 14:00.

1. Introduction

Most secondary osteoarthritis (OA) in a relatively young patient population originates from developmental dysplasia of the hip (DDH). According to national registry data from earlier literature, the incidence of total hip replacement (THR) due to secondary hip OA resulting from DDH is 1%-10% in Europe.

For DDH cases, the acetabulum is usually shallower with an enlarged acetabular angle, resulting in the femoral head's partial or complete exposure. The hip rotational center is shifted laterally and upward, and the upper portion of the femur often exhibits increased antetorsion. This condition affects the normal pressure transfer of the body weight (BW) from the acetabulum downward, resulting in coxa valga. The deformity can also shorten the gluteal muscles, causing weakness in abduction, while increased tension is observed in the flexor and adductor muscles, ultimately leading to the Trendelenburg gait.

The severity of DDH varies widely, ranging from simple dysplasia and subluxation to complete dislocation. Over the years, several classification systems have been reported and applied to assess the deformity severity of the hip joint. Crowe's and Hartofilakidis' classifications have been particularly noted for their excellent inter- and intraobserver reliability and are widely utilized. However, for more accurate surgical planning, particularly in complex cases, further imaging, such as X-rays and CT scans remains essential.

One crucial step during surgery in secondary OA due to DDH is the bone coverage of the acetabular cup. Many surgeons agree that at least 70% bone coverage is required to achieve sufficient primary stability; otherwise, bone grafting becomes necessary. During THR for DDH, the positioning of the acetabular cup shows a vital role in the long-term stability of the components. There is an ongoing debate between surgeons who prefer cemented cups versus uncemented cups. As patients increasingly undergo THR at a younger age, choosing the most suitable approach for acetabular augmentation becomes a more frequent and important decision.

Additionally, while some studies advocate for a high hip center (HHC) position, restoring the primary hip center—or as close as possible to its original location—is generally regarded as the most effective approach to achieving optimal biomechanical alignment for the acetabular cup.

In the context of acetabular augmentation, autologous grafts, particularly those taken from the femoral head, are frequently used for the purpose of the acetabulum reconstruction. This choice is often determined by the surgeon's experience and the available resources. The technique of using the femoral head for grafting was first introduced by Harris in 1977, who described attaching a sculpted bulk bone graft (BBG) from the femoral head to enhance the coverage of the cup in the acetabulum. This inspired lots of different techniques over time. The Roof Step Cut (RSC) technique is also one of them. It originated in our own department and since more than a decade ago it has been used in hip dysplasia surgeries. The principle behind the RSC technique involves creating an L-shaped graft from the resected head of the femur, meanwhile, on the contact area of the acetabulum a stepwise pattern surface should be prepared. The graft is secured with two compression screws at the direction of 45 degrees. This technique is thought to allow the graft and the host bone to have a larger and closer contact area between each other, and the 45-degree angle of the screws is theorized to improve the biomechanical stability of the implant components. However, clinical and mechanical evidence is necessary to validate these theoretical advantages and further support the superiority of the RSC technique over other methods.

2. Objectives

2.1 To comprehensively evaluate a novel orthopedic technique by combining clinical and engineering mechanics analysis.

2.2 To systematically introduce the roof step cut (RSC) technique in detail.

2.3 To conduct clinical research by following up the patients who accepted the total hip arthroplasty surgery with the RSC technique in our department. Record each case's demographic information, follow-up dates, X-ray exam images, laboratory test (if necessary), scintigraphy exam results and so on. With short/mid-term follow-up data, we aim to report the dynamic change of the graft, the rate of graft resorption and cup loosening. By questionnaire investigation, the patients' postoperative functioning conditions also are evaluated.

2.4 To conduct mechanical analysis. Selecting one patient's CT scan data and building up a 3D model of the dysplastic hip. By the finite element analysis (FEA) in Ansys software, the purpose is to compare the RSC technique with the BBG technique, especially focusing on the components' stress distribution, deformation, contact pressure and stability. To demonstrate the beneficial biomechanical features of the RSC technique.

3. Materials and methods

3.1 Clinical study

3.1.1 Patients and methods

This was an observational study. All participants were selected from the Orthopedic Department of the University of Debrecen, Faculty of Medicine. The study was conducted between December 2008 and March 2020. Inclusion criteria were: (1) a confirmed diagnosis of hip dysplasia, (2) A-C severity grade based on the Hartofilakidis classification system, and (3) no objections to the proposed surgical procedures or the research content. Exclusion criteria included: (1) a history of acetabular fracture, (2) bone metabolism disorders caused by tumors or immunological factors, and (3) preoperative X-rays showing significant bone loss in the femoral head, rendering it unsuitable for use as an autograft during surgery. 41 patients (48 hips in total) were included in the study, of whom 39 were female, the average age was 50.1 years old (ranges: 30-75 years old). Written informed consent was obtained from each participant, and all the study content was performed in accordance with the principles of the Helsinki Declaration. The study protocol was approved by the Clinical Center Regional Istitutional Research Ethics Committee (No./Date: DE RKEB/IKEB 5787- 2021).

3.1.2 Surgical Technique

3.1.2.1 Patient preparation

Under general anesthesia, the patient lies supine on the operating table. The dysplastic hip joint was slightly elevated, while adjusting the table keeping the pelvis horizontally. Routine disinfection steps are followed for the preparation and sterile drapes are applied to maintain a sterile field.

3.1.2.2 Exposure

A standard Watson-Jones approach is used to expose the hip joint, which is performed through the natural gap between the gluteus medius muscle and the tensor fasciae latae muscle. Once the joint is exposed, partial capsulectomy was performed. As the hip joint is dislocated, the femoral head is removed using an oscillating saw.

3.1.2.3 Acetabulum assessment

The primary acetabulum should be firstly identified. The condition and bone defect severity are assessed. The smallest diameter reamer is chosen to start reaming. In many instances, following reaming, a triangular defect usually shows up on the inner superolateral region of the acetabulum. Trial cups are then used to evaluate the size and extent of the defect. If more than 30% of the acetabulum remains exposed, bone grafting is usually necessary. The objective of this study is to ensure complete bony coverage of the acetabular cup, even if less than 30% remains uncovered.

3.1.2.4 Host surface preparation

For the RSC technique, based on the size of the defect, it is necessary to perform transverse and longitudinal cortical bone resection at the location of the bone defect on the superolateral side of the acetabulum to expose the cancellous bone and together a rectangular spongiotic surface on the host bone is created. This preparation ensures optimal surface contact for the graft.

3.1.2.5 Graft preparation and fixation

Once the host area is prepared and the size is measured, the femoral head is sculpted into a 90-degree L-shaped graft. Care is taken to preserve as much of the cortical and spongiotic surface as possible. The horizontal portion of the graft is made slightly thicker than the vertical part to facilitate more coverage of the acetabular cup. The graft is then temporarily fixed with

Kirschner wires onto the prepared intra- and supra-acetabular bed. Two compression screws are inserted at 45 degrees for stability fixation.

3.1.2.6 Cup insertion

To ensure a reliable fit between the graft and the acetabular cup, the overhanging portion of the graft is undermined. This allows the proper fit for the metal cup. The size of the cup is rechecked using a trial cup. If the stability is satisfactorily achieved, the final metal cup is inserted using the press-fit technique. If necessary, one or two complementary screws are used for further security.

3.1.2.7 Femoral stem implantation

The femoral medullary canal is prepared using reamers to the ideal size, the final cementless femoral stem is then inserted.

3.1.2.8 Reduction and wound closing

The hip joint is reduced once the final femoral head is implanted. Its range of motion and dislocation tendency are assessed. The surgical area is irrigated with Betadine and saline solution to reduce the risk of infection. Close the wound in layers, and a suction drain is placed, if necessary, to remain for 24-48 hours for postoperative drainage.

3.1.3 Outcome assessment

Postoperative follow-up exams were conducted at 6 weeks, 3 months, 12 months, and then annually thereafter. A standard anteroposterior X-ray of the pelvis was taken every time

for the assessment. The center-edge (CE) angle was defined as the angle between the vertical line through the femoral head center and the inner edge of the graft bone; decrease of the angle indicated the resorption of the bone graft. According to the literature, criteria established by Gruen and DeLee & Charnley were applied for components loosening determination.

To monitor the graft's changes dynamically, 99mTc bone scintigraphy was conducted about 2 weeks after surgery. At 6 months and 12 months post-surgery, the same procedure was used to evaluate the survival of the bone graft. Three-phase bone scans were performed, along with additional single-photon emission tomography (SPECT)/computed tomography

(CT) in the late phase. After injecting 600MBq of 99mTc-MDP radiopharmaceuticals, the first phase started with 60×1-second timing and a 64×64 matrix size, analysis focused on the hip joint area in both anterior and posterior views. The blood pool phase involved a 180-second static scan with the same matrix size and image location. The third phase included a whole-body planar scan in both anterior and posterior views, followed by a SPECT/CT scan of the hip area. All procedures were carried out using a 16-slice SPECT/CT system (AnyScan SPECT/CT, MEDISO). The following parameters were set up for the exam: 128×128-word mode matrix, 64 views at 30 seconds per view, steep and shoot modality, body contouring, and a low-energy all-purpose collimator. The Ordered Subset Expectation Maximization (OSEM) method with a Butterworth pre-filter was used for the reconstruction. In the anterior view of perfusion phase images, circular regions of interest (ROI) were manually drawn around the graft bone area and the reference area on the other side.

For functional assessment, the Western Ontario and McMaster Universities Arthritis Index (WOMAC) and the Oswestry Disability Index (ODI) were used both preoperatively and postoperatively. WOMAC is a widely used tool for assessing hip and knee joint osteoarthritis. It is a self-reported questionnaire with 24 items, categorized into three subscales: pain (5 items), stiffness (2 items), and physical function (17 items). Responses are scored on a scale from 0 to 4, where 0 = none, 1 = mild, 2 = moderate, 3 = severe, and 4 = extreme. Higher WOMAC scores indicate greater pain, stiffness, and functional limitations. The ODI, on the other hand, consists of 10 questions completed by the patient, with responses provided on a six-point Likert scale. 0% indicates no disability, higher scores indicate more severe disability.

3.2 Mechanical study

3.2.1 Reconstruction of the hemipelvis 3D model

Using the CT scan of a 47-year-old female patient with DDH, a 3D pelvis model was reconstructed with Mimics Research 21.0 (Materialise, Leuven, Belgium). In 3-Matic 3D modeling software (Materialise, Leuven, Belgium) the surfaces were smoothed, polished and otherwise optimized, and then a hemipelvis 3D surface model (*stl format) was produced and exported for subsequent FEA model construction. The process involved the following steps:

• Step 1: Importing the CT scan data into 3-Matic software, selecting the coronal plane view. By applying "Segment-Threshold-Bone (CT)" from the menu panel, the bone area on the CT scan is selected.

• Step 2: By clicking the "Region Grow" button, the pelvic (yellow part) is selected. The left femur is also being selected because it has connection with the pelvic.

• Step 3: The target hemipelvis is separated (red region) by the "Split Mask" tool.

• Step 4: By clicking the cubic box as the red arrow showed, the original 3D model is calculated (the "optimal quality" is selected).

• Step 5: Further smoothing, polishing, remeshing the model is done in 3-Matic Medical software.

3.2.2 Assembling the 3D components

Based on the actual dimensions of the solid hip model, the stimulating parts of THA were assembled using the software of Ansys SpaceClaim (2022 R2 version, Canonsburg, USA). The acetabular cup had a diameter of 44 mm, with 20° anteversion and of 40° inclination. The size of the femoral head was 22 mm in diameter.

The shape of the bone graft was set to be irregular to more closely simulate the actual situation during surgery. To minimize size-related errors, the dimensions of the two types of grafts were kept nearly identical. The dimensions of the BBG were 11-19 mm in height, 30 mm in width, and 6-10 mm in depth, while those of the L-shaped bone graft were 15 mm, 30 mm, and 15 mm, respectively. Acetabulum host bone area in the RSC technique model was much larger than the BBG technique model (937.2 mm^2 vs. 674.1 mm^2).

3.2.3 FEA analysis

The FEA was conducted using the software of ANSYS Workbench (2022 R2 version, Canonsburg, USA). Based on the ANSYS material definitions, all components were assigned with corresponding material properties, the Young's modulus (MPa) and Poisson's ratio for the cortical bone is 17300/0.265, for the cancellous bone is 400/0.200, for the titanium is 110600/0.326, for the ceramic linear/femoral head is 350000/0.220.

After importing into Ansys Workbench, the geometries were identified, and mesh was generated. The general mesh size was 3 mm, but at the contact area the mesh size was 0.8 mm to help to achieve more accurate analysis results. Automatic (Solid 187) element type was set up, totaling 365,738 elements and 626,052 nodes were formed. A bonded contact type was selected for most of the interconnections between components. For contacts involving screws, a frictional contact with a coefficient of 0.2 was applied, while for femoral head-linear contact the coefficient was set to 0.1. The contact mesh between the components was matched. The analysis was based on the highest load experienced during jogging, which was set to 3000 N according to the publication. This force was applied perpendicularly to the distal femur cross section surface. The mechanical effects from the muscles were not considered in this study. The sacroiliac joint and pubic symphysis areas were fixed during the analysis.

This study compared two kinds of surgical techniques: (1) the BBG technique, which is based on the original Harris acetabular augmentation technique, and (2) the RSC technique. To evaluate the effect of compression screws, two screws were inserted at 0° or 45° direction for each technique to secure the bone graft. The dimension of the screw was 40 mm in length and 6.5 mm in diameter. As a result, four models were created for the FEA: Harris0, Harris45, RSC0, and RSC45.

The primary analysis focused on the following two aspects: (1) stress distribution and total deformation of bone graft and screws; (2) the pressure and sliding distances at three contact surfaces: bone graft-acetabulum, bone graft-metal cup, metal cup-acetabulum. These interactions were examined to assess the performance and stability of the components in the THA models.

4. Results and discussion

4.1 Clinical study

4.1.1 Patients and methods

41 patients (Female/male:39/2) with 48 hips were included, average age was 50.1 years old (30-75). Because of the poor bone quality, in two patients cemented cups were applied during the surgery, while in the remaining cases cementless cups were implanted. 34 cases were operated unilaterally; the rest were bilaterally. Additionally, half of the hips were classified as Hartofilakidis B type (n=24, type A: n=18, type C: n=6). Patients were followed for an average of 59.6 ± 25.6 months, ranging from 12 to 109 months. No graft resorption cases, while 3 cup loosening were observed.

4.1.2 Postoperative X-ray exam

Postoperative follow-up exams were conducted at 6 weeks, 3 months, 12 months, and then annually thereafter. No signs of graft resorption were observed throughout the follow-up period. The mean center-edge (CE) angles at the first three follow-up time points and the last follow-up were 51.3 ± 3.0°, 50.8 ± 2.6°, 50.6 ± 2.3°, and 49.8 ± 1.8°, respectively ($P > 0.05$). According to the evaluation systems by DeLee & Charnley and Gruen, no radiolucent zones were detected at the interface between the host bone and implants at 12 months post-surgery.

Osteolysis was observed in three cases (7.3%) around the acetabular component and two cases (4.9%) around the femoral component. For the acetabular cups, osteolysis most commonly occurred in DeLee & Charnley II and III Zones, while for the stem it mostly happened in the Gruen VII Zone.

4.1.3 Bone scintigraphy exam

Scintigraphy was conducted at 2 weeks, 6 months and 12 months. 23 patients participated in all follow-up examinations; 4 patients were examined 2 weeks after the surgery, and the remaining 14 patients did not participate in their last follow-up examinations. The mean region of interest (ROI) counts activity ratio (graft vs. reference) for the whole body were 2.14 ± 0.99, 1.52 ± 0.48 and 1.31 ± 0.38 at the three checkup timepoints. For SPECT of the graft, the corresponding values were 0.84 ± 0.31, 0.87 ± 0.42 and 0.99 ± 0.65. The difference for the whole body (H=9.129, P=0.01) was significantly different, and statistically there was a significant difference between the time points of 2 weeks and 12 months (P=0.008). However, no significant difference between the groups was revealed for the SPECT (H=0.189, P=0.910). After the surgery, bone graft showed gradual increase of activity, at 12 months it became almost the same as the reference site.

4.1.4 Function and disability evaluation

The WOMAC and ODI scores showed significant improvement after surgery. The average ODI decreased from 36.6% (ranging from 25% to 40%) preoperatively to 16.8% (ranging from 12% to 20%) in the end ($P < 0.05$). The mean WOMAC score also showed significant improvement (from 88.3 points decreased to 38.0 points, $P < 0.05$). Three cases required cup revision due to loosening. Two of these revisions followed high-energy trauma to the operated hip, which were revised with cemented and cementless cups separately. For the third case, an aseptic loosening was caused by metastatic colon cancer in the acetabulum.

After careful consideration and discussion, a Girdlestone procedure was eventually performed. No complication was identified directly caused by the technique.

4.2 FEA biomechanical study

4.2.1 Stress distribution and deformation of the bone graft

The maximum stress values for the Harris0, Harris45, RSC0, and RSC45 models are 97.13 MPa, 112.72 MPa, 16.56 MPa, and 25.50 MPa, respectively. The stress in the Harris models is considerably higher than in the RSC models. A similar trend is observed in total deformation, with the maximum values being 0.022 mm, 0.018 mm, 0.0096 mm, and 0.0089 mm, respectively. The grafts with 45° inserted screws exhibit higher stress and smaller deformation compared to those with 0°inserted screws.

Screw insertion angle seems to have an effect on the maximum value location in both models. Generally, 0° inserted screws generate the highest stress in the graft, closer to the contact between the bone graft and the acetabulum, while for screws inserted at a 45° angle, the highest value is located more laterally at the edge of the graft, which, in reality corresponds to the cortical bone shell that offers greater resistance strength.

4.2.2 Stress distribution and deformation of the screws

Based on the results of FEA analysis, the maximum von Mises stress distribution in the screws from the model of Harris0 to the model of RS45 is 97.13 MPa, 112.72 MPa, 16.56 MPa, 25.50 MPa, respectively. The values in the RSC models are significantly lower than those in the Harris models. The maximum total deformation follows a similar trend. During the study, it is observed that when the screws are inserted at 0°, the highest value is located close to the center of the screw, while when inserted at 45°, the highest value moves to the outer 1/3 area of the screws.

4.2.3 The pressure and sliding distance at different contact surfaces

Three contact areas were analyzed: the graft-host bone contact (first row), the graftmetal cup contact (second row), the metal cup-acetabulum contact (third row). Overall, the maximum pressure and sliding distance shows a decreasing trend from models of Harris0 to RSC45. When the BBG is fixed with screws at 45 degrees (the Harris45 model), the contact between the metal cup and the acetabulum shows notable instability with larger sliding distance. Also, the pressure at the bone graft-metal cup contact is presented with a significant high value (276.2 MPa, Harris0:153.0 MPa, RSC0:1.06 MPa, RSC45:1.02 MPa). The maximum pressure and sliding distance values differ between the two models. It is located more centrally in the BBG model while more marginally near the edge in the RSC model.

5. Main findings

• Roof step cut technique is a feasible method to reconstruct the acetabular roof for hip dysplasia cases. The short/mid-term clinical outcome is satisfactory. It does not require special skills or devices to perform the procedure.

• For highly dislocated or difficult cases, it is recommended to take a CT exam before the surgery. On one hand, to have a more intuitive understanding of the overall condition of the acetabulum: on the other hand, if the femoral head is too small or there are big subchondral cysts inside of it and autograft will be impossible, then allograft or other implants could be prepared in advance.

• Bone scintigraphy could help to evaluate the graft viability. Postoperatively at different time points it can present with dynamic changes showing increasing diffuse activity accumulation in the graft bone area. Exams at 2 weeks after the surgery can effectively avoid the interference caused by the soft tissue oedema.

• The "L-shaped" grafts resulted in larger contact areas between the graft and host bone. When compared to traditional BBG, the RSC technique effectively reduces stress and deformation on both the graft and compression screws. Additionally, it decreased the pressure and sliding distance at the contact surfaces between the components. Screws inserted at a 45° angle produced higher stress concentrations at the ends of the screws which contacted the outer cortical bone of the graft, making it less likely to cause screw breakage or component loosening. Overall, from a mechanical perspective, the RSC technique offers distinct advantages.

6. Authenticated list of Candidate's Publications

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Registry number: DEENK/36/2024.PL
Subject: PhD Publication List

Candidate: Lei Zhang
Doctoral School: Doctoral School of Clinical Medicine

List of publications related to the dissertation

1. **Zhang, L.**, Rashwan, A., Manó, S., Szabó, J., Mankovits, T., Csernátony, Z.: Biomechanical Comparison of the Roof Step Cut Technique with the Bulk Bone Graft Technique During Total Hip Arthroplasty for Hip Dysplasia: a Finite Element Analysis.
Acta Chir. Orthop. Traumatol. Cech. 90 (4), 329-341, 2023.
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2. Csernátony, Z., Győrfi, G., Barna, S., Manó, S., Szabó, J., **Zhang, L.**: The roof step cut: a novel technique for bony reconstruction of acetabular roof deficiency during total hip replacement.
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DOI: http://dx.doi.org/10.52312/jdrs.2022.266
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3. **Zhang, L.**, Lu, X.: Acetabular Cup Positioning during Total Hip Replacement in Osteoarthritis Secondary to Developmental Dysplasia of the Hip: a Review of the Literature.
Acta Chir. Orthop. Traumatol. Cech. 86 (2), 93-100, 2019.
IF: 0.256

List of other publications

4. Kovács, Á. É., Csernátony, Z., Csámer, L., Méhes, G., Szabó, D., Veres, M., Braun, M., Harangi, B., Serbán, N., **Zhang, L.**, Falk, G., Soósné Horváth, H., Manó, S.: Comparative Analysis of Bone Ingrowth in 3D-Printed Titanium Lattice Structures with Different Patterns.
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14. Wu, H., Chen, Y., Wang, Z., Li, W., Li, J., **Zhang, L.**, Lu, Y.: Involvement of p21 (waf1) in merlin deficient sporadic vestibular schwannomas.
    Neuroscience. 170 (1), 149-155, 2010.
    DOI: http://dx.doi.org/10.1016/j.neuroscience.2010.06.051
    IF: 3.215

Total IF of journals (all publications): 14,687
Total IF of journals (publications related to the dissertation): 2,256

The Candidate's publication data submitted to the iDEa Tudóstér have been validated by DEENK on the basis of the Journal Citation Report (Impact Factor) database.

06 February, 2024

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