DISSERTATION FOR THE DEGREE OF DOCTOR OF PHILOSOPHY (PHD)

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

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The list of abbreviations

BBG	Bulk bone graft
BMI	Body mass index
BMPs	Bone morphogenic proteins
BW	Body weight
CE	Center-edge
CT	Computed tomography
DDH	Developmental dysplasia of the hip
FEA	Finite element analysis
HHC	High hip center
ISG	Intraosseous Structural Graft
MIP	Maximum intensity projection
MSCs	Mesenchymal stem cells
OA	Osteoarthritis
ODI	Oswestry Disability Index
OSEM	Ordered subset expectation maximization
PRC	Primary rotational center
ROI	Regions of interest
RSC	Roof step cut
SPECT	Single-photon emission tomography
THA	Total hip arthroplasty
THR	Total hip replacement
TM	Trabecular metal
WOMAC	Western Ontario and McMaster Universities Arthritis Index

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[1].

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[2].

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[3-6]. 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[7]. 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[8, 9], 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[10].

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[11]. 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. Literature review

2.1 Hip dysplasia

The hip joint is a synovial ball-and-socket joint, it undergoes a series of dynamic changes as it develops. In the embryonic stage, the shape of the femoral head is round like a sphere, the femur neck is short with a rudimentary greater trochanter. Along with the skeleton's development, the femoral head gradually changes its position and locates centrally into the cup-shaped acetabulum, which normally faces in the antero-lateral direction in the pelvis[12]. With stability provided by the joint capsule, it can allow for a wide range of movement as well as transmit the BW to the lower limbs. The acetabular labrum at the outer rim of the acetabulum through the "seal-suction" effect helps to stabilize the femoral head in its position.

DDH is a pathological change in the maldevelopment of the hip joint. The acetabulum is usually shallower or incorrectly oriented, sometimes combined with flaccid ligament and weak muscle strength. The normal loading mechanism across the hip joint is disrupted. Over time the acetabular labrum hypertrophied in order to compensate for the bony deficiency, which makes it much easier to get injured or torn[13]. Subsequently, the suction seal effect which typically helps maintain hip joint stability is lost, resulting in further pathological development. Therefore, the femoral head gradually deviates from the position of the original rotation center[14]. Since the interaction between the femoral head and joint cartilage is missing, dysplastic femur has been shown with a shorter neck, a smaller and straighter canal, increased anteversion and aspheric femoral head with characteristic and variable dependent on the severity of dysplasia. Anteversion or retroversion of the femoral shaft, femoral neck's inclination, altogether causing valgus deformity of the hip.

Along with these pathophysiological changes, dysplastic hip could develop into secondary hip osteoarthritis(OA) much faster compared to a normal hip joint. The patients may have multiple treatments or surgeries throughout their life and have been asymptomatic for a number of years. Regardless of the age at which it occurs, hip dysplasia is directly associated with early development of hip OA, most patients will undertake arthroplasty surgeries to improve their life quality.

The incidences reported in Europe are highly variable, ranging from the lowest in the United Kingdom (3.6 per 1000) to the highest in Eastern Europe (35.8 per 1000)[14]. However, a recent study carried out in Hungary has shown that on the first ultrasound examination after birth, which took place in the first 1-4 days, among the totals of 3272 hips examined the authors found positive findings in 70 cases (2.14%)[15].

2.2 Etiology

The etiology of DDH is still unknown. Significant variability in incidence has been reported in the literature[16]. The reasons attributed to this include: (1) there is a lack of uniform standards and consensus on the best time and method for screening; (2) different diagnostic protocols are used across countries and continents. It has been reported that the occurrence of DDH was rarer in Asia and Africa than in Europe and America, because for the first two racial groups, in the early postpartum period mothers usually carry their babies on their backs in a position like the Pavlik harness and continue their daily activities[17, 18]. Given that the cause of hip dysplasia can directly affect the specific treatment plan, a careful examination of the family history of the child is required in clinical practice to rule out the influence of neuromuscular diseases and other factors[19]. Figure 1 showed the factors related to the DDH incidence. Among all risk factors, breech presentation was the most significant, with an associated incidence of DDH of nearly 30%. Interestingly, children born prematurely, with low birth weight, or to multifetal pregnancies are somewhat protected from DDH.

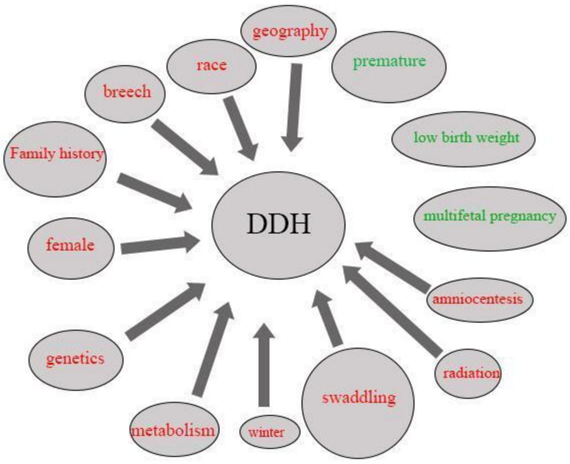


Figure 1. Factors related to the occurrence of DDH

2.3 Biomechanics based on Pauwels' theory

Pauwels established the modern theory of hip biomechanics based on graphics and simulation models[20]. Bone structure and soft tissue abnormality could adversely affect the biomechanics of the hip joint. Positional deviation of femoral head in cranial direction increases stress distribution on the acetabular rim. Overload and repetitive motion could eventually lead to early cartilage damage and degeneration, the development of secondary osteoarthritis. Due to these pathological changes, the shallow acetabulum will be unable to fully cover the femoral head. Given that this often occurs in a relatively young patient population, it can significantly impact the patient's quality of life.

The negative effects of cranial and lateral movements of the femoral head can be explained by Pauwels’ theory. G represents the force of the BW exerting on the hip, L2 is its lever arm (≈12cm). F represents the balance force from the abductor muscles, with L1 as the lever arm (≈3cm). R represents the vectorial sum of forces G and F, which is transmitted by the hip joint. Therefore, force R could be more than 4 times BW during normal walking. Normally, the hip joint evenly bears this compressive force at its surface. The red ribbon indicates the subchondral sclerosis at the area of the acetabulum roof. (Figure 2a)

In hip dysplasia cases, the abductor muscle’s lever arm (L) becomes shorter, therefore, the muscles have to develop more strength to keep the BW in balance (> 3 times). The compressive force R’ increases at the same time, and since the action line of the muscles is closer to vertical, force R also moves to the lateral region of the socket and the joint weight bearing surface decreases. Altogether, the joint pressure will be increased and the more pronounced the subluxation, the higher the dense triangle corresponding to the stress diagram. This explains why dysplastic hips progress to osteoarthritis more quickly and how joint deformities develop. (Figure 2b)

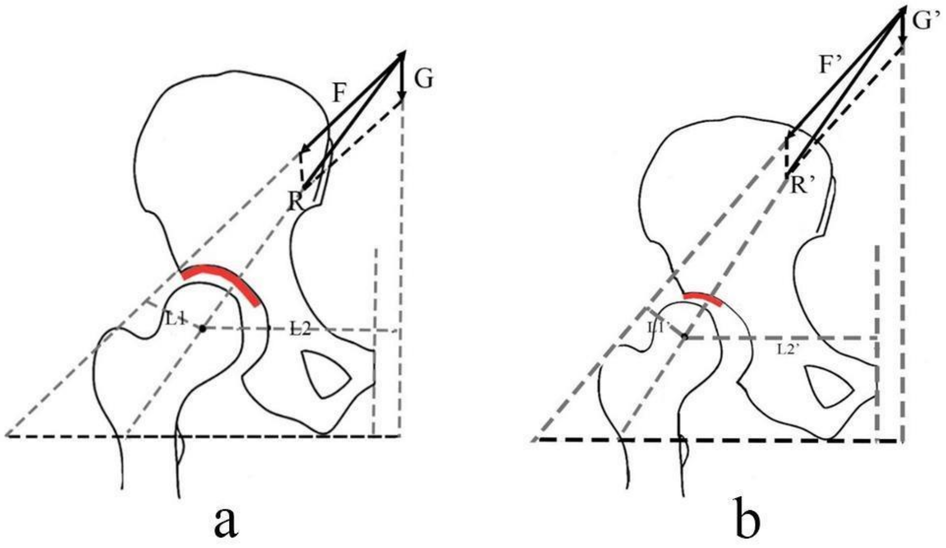


Figure 2. Diagram of Pauwels' hip biomechanics. (a) normal hip; (b) dysplastic hip

2.4 Symptoms observed in a clinical setting

Because of the secondary osteoarthrosis and difference in the lower limb length caused by the femoral head cranial movement, the joint could not function properly for hip dysplasia patients. Most of them will present with characteristic clinical symptoms[21, 22], as shown in Figure 3. Conservative therapy to some extent could help relieve the symptoms, however, the patient's quality of life is still adversely affected by this pathological condition.

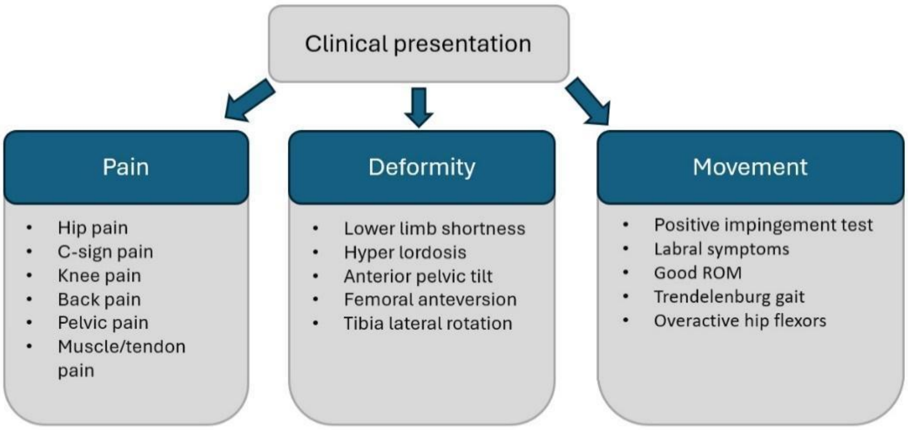


Figure 3. Summary of clinical manifestations of developmental dysplasia of the hip

2.5 Evaluation and classification

Different classification systems have been reported to determine the severity of DDH. Among them three methods are most used, which are the lateral center-edge angle (LCEA)[23], Crowe's and Hartofilakidis's classifications.

Wiberg[24] firstly described the LCEA, on a standard pelvic anteroposterior radiograph, the whole femoral head is outlined with a circle. Then draw two straight lines passing through the circle's center, one is parallel to the longitudinal axis of the pelvis and the other passes through the lateral superior margin of the acetabulum. LCEA is the angle formed by these two lines (Figure 4). which can indirectly reflect the degree of femoral head exposure. The angle less than 20° indicates acetabular dysplasia; 20°~25° indicates a tendency toward acetabular dysplasia; 25°~40° indicates normal condition; the angle larger than 40° indicates pincer morphology of femoroacetabular impingement.

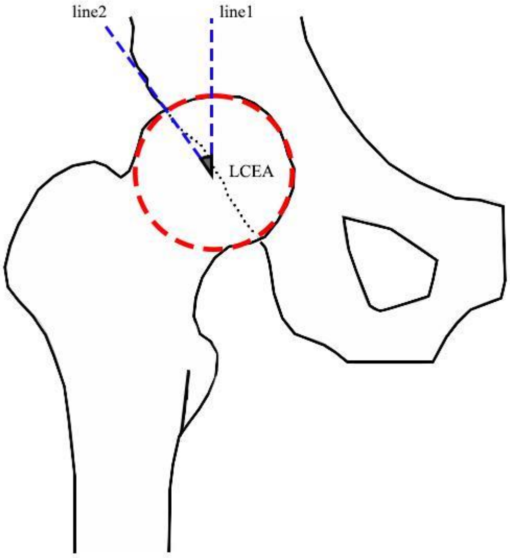
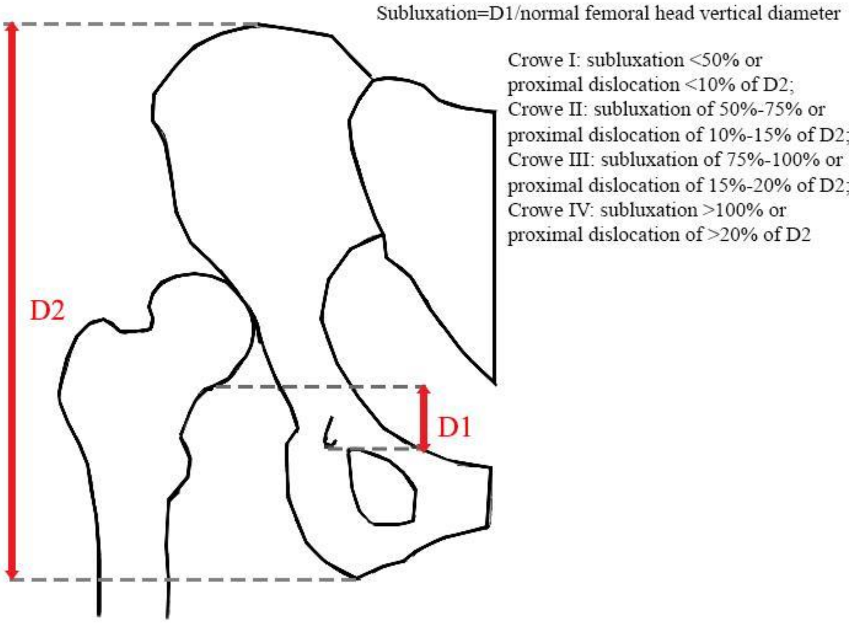


Figure 4. Lateral center-edge angle (LCEA). Line 1 is parallel to the longitudinal axis of the pelvis; Line 2 is crossing the lateral superior margin of the acetabulum

Crowe's classification evaluates DDH based on the cranial shift of the femoral head. Two landmarks should be identified on the standard anteroposterior pelvic X-ray image, one is the inter-teardrop line, and the other is the junction of femoral head and neck. The ratio of the vertical distance between these two sites to the normal vertical diameter of the femoral head reflects the degree of subluxation. Another important landmark is the pelvis height, which is the vertical distance from the top of the iliac crest to the lowest point of the ischial tuberosity (Figure 5). Crowe classified subluxation and proximal dislocation of pelvic height into four grades, with higher grades indicating more severe dysplasia[25].



Subluxation=D1/normal femoral head vertical diameter

Crowe I: subluxation <50% or
proximal dislocation <10% of D2;
Crowe II: subluxation of 50%-75% or
proximal dislocation of 10%-15% of D2;
Crowe III: subluxation of 75%-100% or
proximal dislocation of 15%-20% of D2;
Crowe IV: subluxation >100% or
proximal dislocation of >20% of D2

Figure 5. Crowe classification I-IV. D1: distance between the inter-teardrop line and the femoral head-neck junction; D2: pelvis height, vertical distance from the top of the iliac crest to the lowest point of the ischial tuberosity

In 1988, Hartofilakidis et al.[26] published the classification system for hip dysplasia based on the femoral head and acetabulum morphological changes. From type A to type C the femoral head gradually moves cranially in the acetabulum until totally high dislocation. (Figure 6)

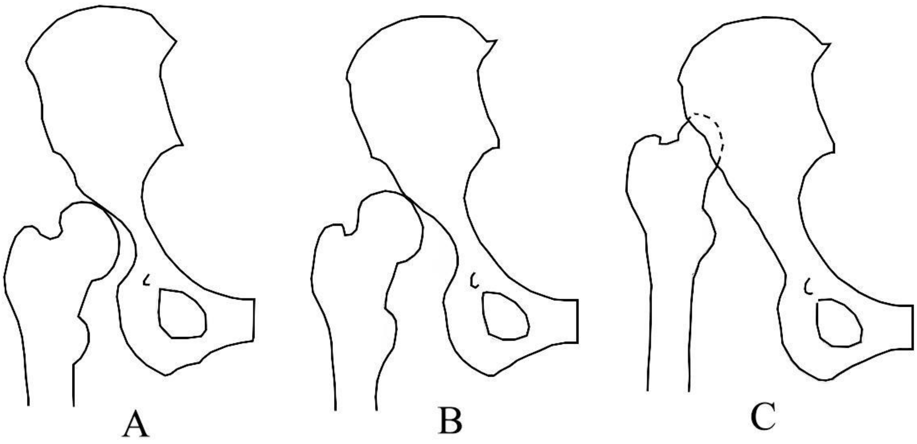


Figure 6. Hartofilakidis classification: A dysplasia, B low dislocation, C high dislocation

2.6 Total hip arthroplasty (THA) surgery techniques

For DDH patients with secondary hip osteoarthritis, when non-operative intervention has failed, total hip arthroplasty (THA) is a frequently chosen solution to help to improve patients' symptoms and enhance joint function. Compared to the HHC, the primary rotation center restoration is more widely preferred, because of the better joint kinematics, biomechanics and more stable bone-implant interface. Cranial movement of the rotation center is accompanied by a series of changes like the shorter lower limb length, weaker muscle activity, causing impingement and gait disturbance. It is also believed that the component wear rate appears to be much higher in this condition[27]. Cement or cementless techniques are also controversial topics concerning THA for dysplastic patients. Considering that most patients present with the complaints at relatively young age and it's quite possible that revision surgeries are needed later in their lives, "press-fit" cementless cups are usually favored by most surgeons. On one hand, cemented implant revision surgery is more challenging, extra bone loss is inevitable during the removal of the component. On the other hand, when using autograft to reconstruct the defective acetabulum, the cement could inevitably be suppressed into the space between the acetabulum and the graft bone, adversely affecting the bone incorporation process, leading to earlier loosening. The surgery itself could be very challenging because of the superior lateral defect as well as the shallowness of the acetabulum. Reconstruction is suggested if more than 30% of the acetabulum is missing[7]. Different techniques in the literature have been reported about how to reconstruct the acetabulum, which could be categorized into several groups.

2.6.1 Bulk bone graft

When bone graft is needed, autograft is considered as the "gold standard", because it owns the natural structural properties, autologous cells and factors which will be helpful for the graft's integration to the host bone. It also has the advantages of fast healing, inexpensive, no disease transmission or initiation of the host's immune reaction. But the availability of the autograft is usually limited, the operation time is longer, and it could also cause donor site morbidity. Allograft bone comes from a bone bank. It needs to go through the process of sterilization and demineralization, during which the calcium and other minerals will be removed, the left collagen and proteins (including bone morphogenetic proteins, BMPs) could be osteoinductive. It has advantages like no donor site morbidity, decreased operation time, large variety of graft sizes and shapes. However, it is also expensive, has the risk of disease transmission, immune response and rejection, ethical and religious concern and so on[28].

In 1977 Harris et al.[11] initially reported the BBG application for the acetabular roof reconstruction in dysplastic cases. The grafts were cut from the femoral heads (Figure 7). However, later because the revision rate was too high, they withdrew the promotion of this technique. From today's perspective, the poor clinical outcomes may be related to the limited quality of the technique and prostheses used at the time. Since then, this technique has been widely used and developed. In Masui's[29] study 21 DDH were included, BBG sculpted from the resected femoral head was applied. The average acetabular cup coverage provided by the graft was 23.1%. Three cup loosening cases were identified after an average 12-year follow-up, however, none of them needed revision surgery. Another study by Shimamura[30] showed that although the average bone coverage index was 44.4% and the average LCEA was -17.8°, bulk femoral head autografts could provide reliable reinforcement of the acetabular roof. Cementless THA showed good long-term outcomes and graft viability. Delimar et al.[31] included 72 dysplastic hips in 64 patients that underwent THA with bone grafts from different sources, all cases were assessed with a 10-year follow-up after operation. Results showed that regardless of the bone graft type, the prognosis of the cemented THA was much worse than the cementless technique. Further, autografts showed half as rapid failure as allografts. In Oe's study[32] they analyzed three different shaped BBG techniques in cemented THA for DDH patients, they reported that with more than ten years' follow-up, all the grafts were well integrated with the host bones, and no revision or loosening was noted.

As shown above, the clinical outcome of the BBG technique is still controversial. Different studies have reported various results, the possible reasons behind this include: (1) Study subjects characteristics difference, for example, factors like age, gender, bone quality, activity level, nutrition, society and economic status, systematic medical history, etc. All these could affect the clinical results. (2) The follow-up time and evaluation standards are inconsistent. (3) The spectrum of sample size difference is quite large. However, autologous BBG harvested from the femoral head still remains to be the most convenient and cost-effective way during clinical practice. Sometimes because of the degenerative changes of the femoral head, like cysts or sclerosis, the strength or size is not adequate to be used as bone graft, other alternative sources need to be considered.

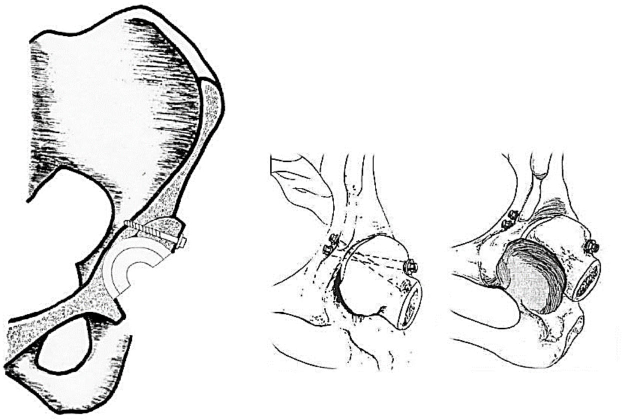


Figure 7. Harris' original bulk bone autograft technique

2.6.2 Procedures related to the iliac bone

2.6.2.1 The iliac crest bone graft

The iliac crest is another common source of autologous bone grafts. It can provide large amounts of bone, which meets the requirements of large defect reconstruction of the acetabulum[33]. The main complication of this technique is donor site pain, chronic pain is found in up to 30% of the patients (Figure 8). Except for the simple graft, the vascularized bone graft technique has also been reported. Vascularized bone grafts have been studied in numerous experimental and clinical reports compared with the non-vascularized grafts. Bone grafts with blood supply could integrate with the host bone more rapidly and adapt better to new biomechanical environments, therefore, their survival rates are relatively higher. The vascularized iliac graft contains viable osteogenic cells, especially in the medullary bone, which can significantly increase the metabolic activity of the tissue, facilitate the formation of new bone, and promote the fusion of bones. The graft could either be vascularized by the deep circumflex iliac vessels or the sartorius muscle, both have been proved sufficient to provide an acetabular coverage[34]. The lateral femoral cutaneous nerve should be identified and protected during the surgery, and for cosmetic reasons the anterior superior iliac spine should be kept intact.

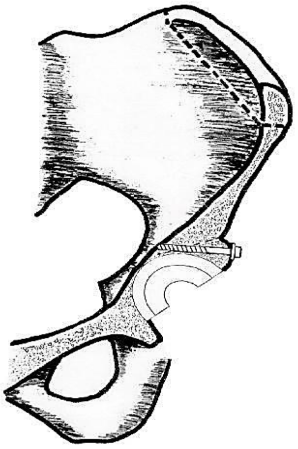


Figure 8. Autologous iliac crest bone graft technique

2.6.2.2 Iliac sliding graft technique

A rectangular osteotomy is made at the outer iliac surface with an oscillating saw and an osteotome. Leaving the medial cortex of the ilium intact. Separating the outer part of the ilium from the medial cortex, sliding it down to the level of the superolateral acetabular rim. The graft is fixed with two cancellous screws. After reaming a proper bone graft support for the cup is achieved (Figure 9). It is reported that when the patient's own femoral head is not ideal to use, this technique deserves consideration as an alternative. Clarke et al.[35] reported that the mean time for osteointegration was 12 months. Ikeuchi et al.[36] reported that incorporation of the iliac sliding graft was seen after two to three months in all 19 dysplastic patients. And the author believed that the reason behind it was the intimate host-graft contact and rigid stability. However, during this procedure there is risk for the superior gluteal nerve injury, causing postoperative abductor dysfunction.

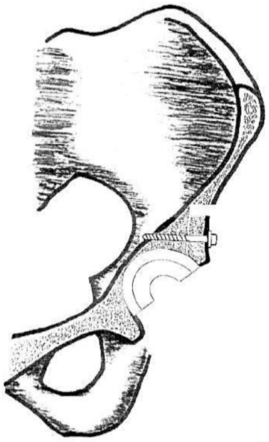


Figure 9. Iliac sliding graft technique

2.6.2.3 Intraosseous structural graft technique

Szabó et al.[37] reported this technique in 2013. During the operation, a cortico-spongious plate is made at the bone defect area of the dysplastic acetabulum, where the proximal end is fixed. Gently bend the distal end of the plate until proper coverage of the metal shell is achieved. The bone graft is shaped into a wedge with a size similar to the space under the bone plate. Impacting the graft under the cortico-spongious plate, two cortical screws are inserted to provide sufficient stability. 19 hips from 10 cadavers were included and through biomechanical analysis of the components the author concluded that this technique could achieve good fixation of the acetabular cup and theoretically provide an appropriate environment for osteointegration. (Figure 10)

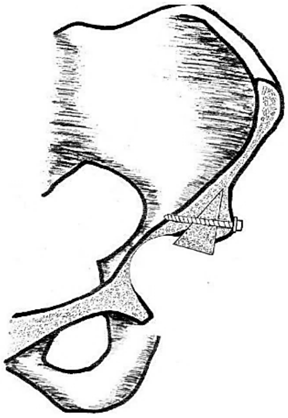


Figure 10. Intraosseous structural graft（ISG）technique.

2.6.2.4 Medial wall protrusion technique

The technique which purposefully perforates the medial wall of the dysplastic acetabulum is rarely used nowadays. Earlier, as an alternative solution, Dunn and Hess[38] reported that this technique could permit good coverage of the acetabular component without bone-graft support. By breaking through the cortical bone of the acetabulum fossa, the acetabular component will locate medially to the Kohler line on the radiograph (Figure 11). In 1978 the initial study included 17 patients, at an average of three-year follow-up, no case showed components loosening. With using the protrusion technique and cement, Hartofilakidis et al.[39] included 86 hips for an average of 7-year follow-up, two cups were revised and two cups showed migration. The medial wall perforation could be done with an osteotome, or some surgeons prefer with a reamer. Technically, the defect should remain only at the medial point of the acetabulum, and it should not exceed 25% of the acetabulum area. A certain amount of bone mass needs to be preserved in other parts of the acetabulum during reaming, otherwise, the metal shell press-fit insertion could cause acetabular fracture, leading to instability of the reconstruction[40, 41].

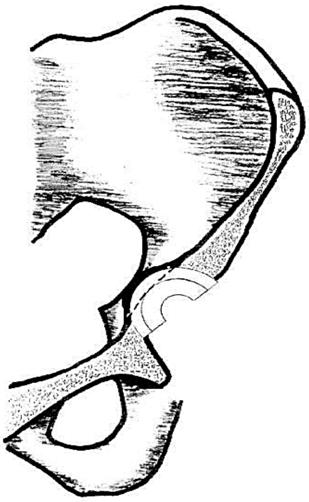


Figure 11. Medial wall protrusion technique (cotyloplasty)

2.6.3 Special cups, augments

2.6.3.1 Porous tantalum augment

Serving as an alternative to allograft, it does not have the potential of resorption and disease transmission. Osteoconduction and osteointegration could be advantageously achieved because of the unique properties of the material. The porous structure is suitable for the migration of osteoblasts, and the mechanical parameters such as elastic modulus also make it have good bearing capacity and mechanical conduction[42] (Figure 12a). With better physical load transferring mechanisms, bone stock could be relatively better preserved. Good to excellent early clinical results have been reported about its application during THA when the acetabulum showed severe bone loss. Some authors believe that especially when there was an intact acetabulum still in continuity, this implant showed excellent long-term survivorship[43]. Although different sizes are available to choose from during clinical practice, sometimes the shape of the augment could not perfectly match the bone defect, therefore, the reconstruction is not fully accurate.

2.6.3.2 Oblong cups

An oblong cup is preferred when the acetabulum presents with an oval bone defect, which means the longitudinal diameter is larger than the transverse (Figure 12b). In this case, conventional implants no longer meet the need of acetabulum reconstruction. The oblong cup can not only achieve good stability with minimal bone mass loss of acetabulum, but also preserve the mechanical axis of the acetabulum, which is further beneficial to the transmission of load bearing. Because of its special shape, the primary rotation center is relocated, and the excessive superior placement of the cup is avoided. Most studies have shown good clinical results for oblong cups[44, 45].

2.6.3.3 Jumbo cups

A Jumbo cup is usually chosen when there is a large defect on the acetabulum. The minimum diameter of the cup is 62 mm or 10 mm larger than the normal acetabulum diameter (Figure 12c). The advantage is that additional structural bone graft or cement is not needed. Study has shown that porous jumbo cups could provide satisfactory long-term clinical outcomes and usually require additional screws fixation for further reinforcement[46]. However, the anatomical rotation center fails to be restored, and the anterior and/or posterior column is sacrificed, which causes significant challenges for the revision surgery in the future[47].

2.6.3.4 Bilobed cups

Bilobed cups are like oblong cups. They are an alternative to jumbo cups and have advantages such as increasing contact area with the acetabulum host bone, avoiding bone loss caused by excessive reaming, ensuring component stability without the need for additional augment, and the restoration of the primary rotation center makes the overall mechanical structure more stable[48] (Figure 12d). Study by Moskai et al.[49] showed that for revision cases with Type III acetabular defect porous coated bilobed acetabular cups can achieve satisfactory clinical results in mid-term follow-up.

2.6.4 3D printing

3D printings like the navigation plate and customized prosthesis have been reported and used in THA for DDH[50] (Figure 12e). With the help of navigation plates, errors could be effectively reduced due to lack of experience and immature surgical techniques. In the field of orthopedics, many studies have reported that 3D-printed guiding devices could increase the safety of internal screw and plate fixation. However, its application in THA is still limited. Yan et al.[51] reported that based on the false acetabulum, a circular guide plate was designed and located at the true acetabulum, the detachable base and ring could be conveniently applied during the surgery. The author concluded that this device was more accurate than most of the other techniques, with decreased operating time, perioperative complication rate, and better postoperative function outcomes. By using individualized design and additive manufacturing (AM) methods, Zhang et al.[52] applied a novel 3D printed integral implant in THA for a patient with DDH Crowe type III. By electron beam melting technology a wing part was designed on the prosthesis to match the defective part on the acetabulum to help to achieve the anatomical rotation center reconstruction. They found that the 3D printed prosthesis could perfectly fit into the acetabulum, the defect part was properly fixed. The 12-month follow-up result was satisfying. Furthermore, for cases needing additional screw fixation, the direction and position of the screws could also be designed in advance with the help of the software, making preoperative preparation more adequate and improving the intraoperative safety and efficiency. The patient-specific prosthesis fabrication requires careful preoperative planning, extensive clinical experience and advanced 3D technology, in this process ethical issues are inevitable due to the individual and technological variations. Indications and standards are still worth exploring for its clinical applications in the future.

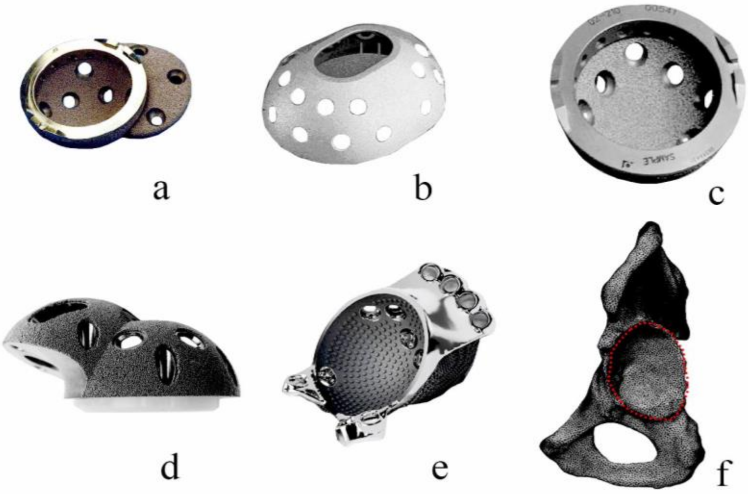


Figure 12. Special cups/augments available to reconstruct the dysplastic acetabulum. (a) porous tantalum augment; (b) oblong cup; (c) jumbo cup; (d) bilobed cup; (e) 3D printed cup; (f) the typical dysplastic acetabulum (red dots closed area), because of the irregular shape, special implants above mentioned are necessary sometimes

In summary, DDH is mainly characterized by a shallow acetabulum, increased acetabular angle, proximally migrated and deformed femoral head, and muscle imbalance issues. Due to its biomechanical mechanism, OA could be developed much faster and earlier for a dysplastic hip joint, which will significantly affect the patient's quality of life. Most of them will undertake THA at a relatively young age. Many different treatment techniques have emerged over time, each with different advantages and disadvantages. The basic concept is by increasing the coverage of the cup to achieve stability, including the use of special implants.

3. Objectives

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

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

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.

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.

4. Materials and methods

4.1 Clinical study

4.1.1 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).

4.1.2 Surgical technique

4.1.2.1 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.

4.1.2.2 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.

4.1.2.3 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 (Figure 13a). 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.

4.1.2.4 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 (Figure 13b-d, Figure 14). This preparation ensures optimal surface contact for the graft.

4.1.2.5 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 (Figure 13e, f). 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 (Figure 13g).

4.1.2.6 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 (Figure 13h). 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 (Figure 13i).

4.1.2.7 Femoral stem implantation

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

4.1.2.8 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.

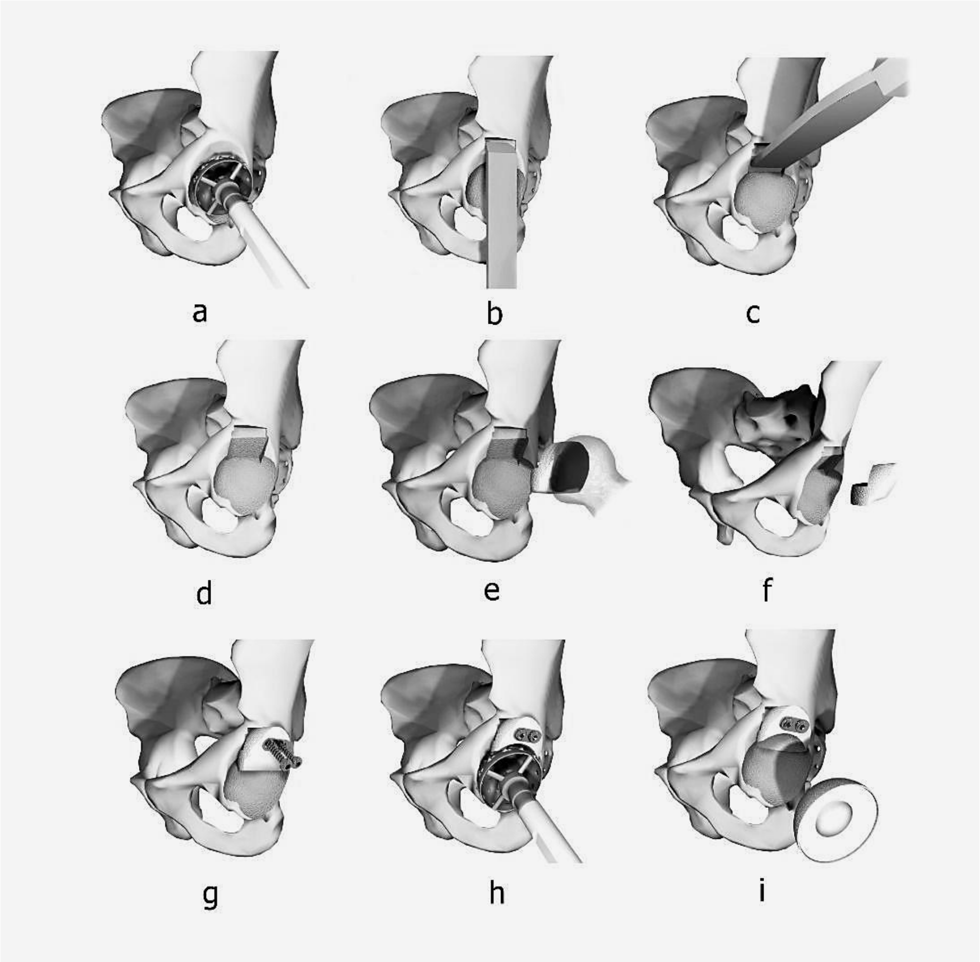


Figure 13. The RSC technique. After assessing the acetabulum, start reaming with a small-diameter reamer (a) , vertical and horizontal cut is performed to create a spongiotic host surface at the bone defect area of the acetabulum (b, c, d), then according to the required size, sculpt the femoral head into a 90-degree “L” shaped bone graft, with cortical bone surface preserved (e, f). After fixing the graft with two compressing screws at 45-degree angle, ream the acetabulum again to remove extra bone from the graft (g, h) and finally a spongiotic acetabular contact surface with high coverage is created and the cementless metal cup is inserted by the “press-fit” technique

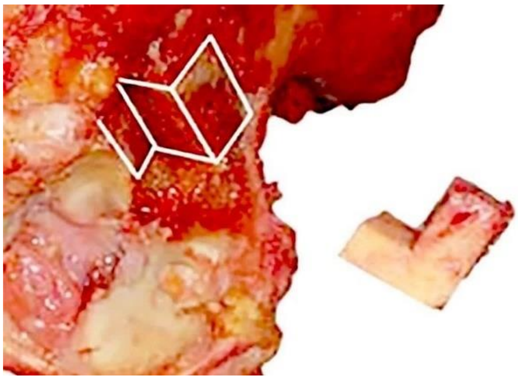


Figure 14. The "L-shaped" graft and the matching surface of the host bone from a cadaver model

4.1.3 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. Figure 15a showed the method to evaluate the bone graft resorption. 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[53, 54], as Figure 15b illustrated.

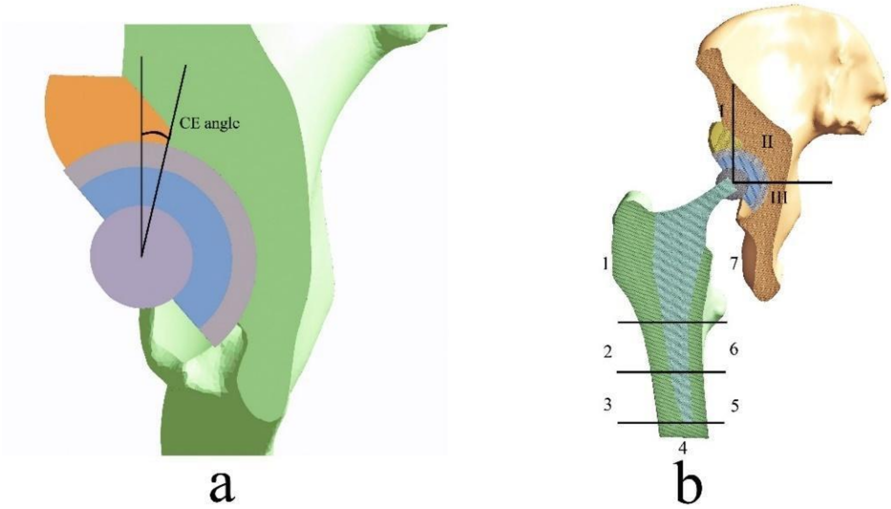


Figure 15. (a) Cup center-edge angle: the perpendicular line is parallel to the longitudinal axis of the pelvis and the other line is drawn from the center of the head to the lateral edge of the acetabulum**.** (b) Zones of DeLee and Charnley (I-III) and Gruen (1-7) methods to evaluate loosening components

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[55]. 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. Figures 16 and 17 show the comparison of the activity ratio between the two areas.

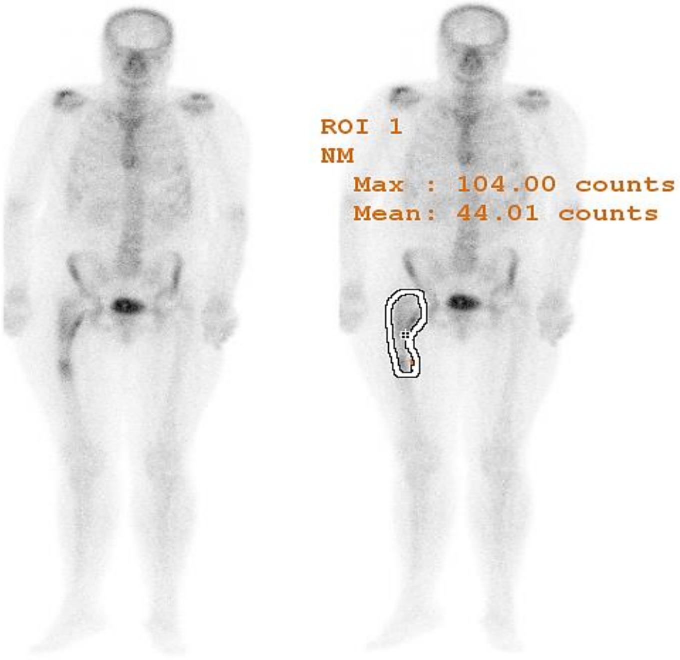


Figure 16. On static/whole body images, the circular regions of interest (ROI) is drawn and the counts is measured

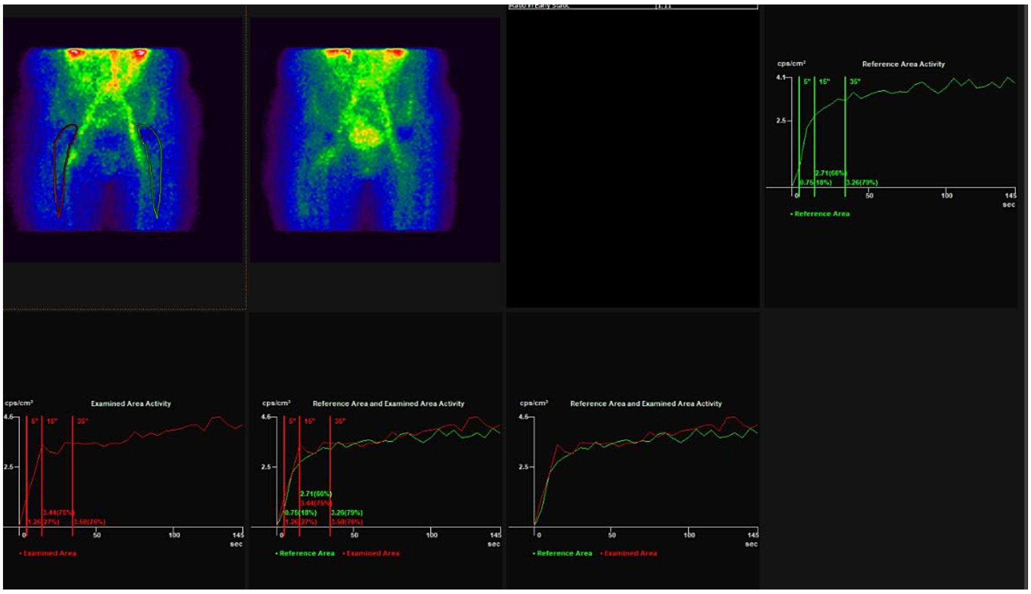
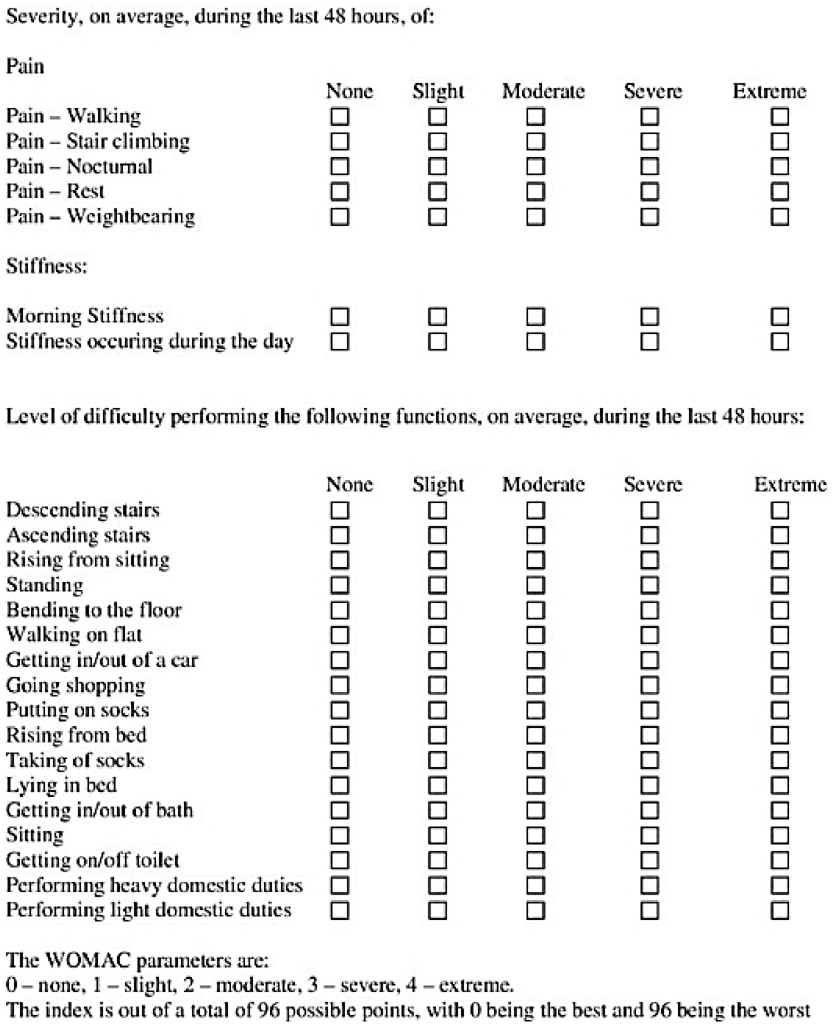


Figure 17. On dynamic images circular regions of interest (ROI) is drawn and the counts are drawn on time activity curves

For functional assessment, the Western Ontario and McMaster Universities Arthritis Index (WOMAC)[56] (Figure 18) and the Oswestry Disability Index (ODI)[57] (Figure 19) 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.



Severity, on average, during the last 48 hours, of:

Pain

	None	Slight	Moderate	Severe	Extreme
Pain – Walking	☐	☐	☐	☐	☐
Pain – Stair climbing	☐	☐	☐	☐	☐
Pain – Nocturnal	☐	☐	☐	☐	☐
Pain – Rest	☐	☐	☐	☐	☐
Pain – Weightbearing	☐	☐	☐	☐	☐

Stiffness:

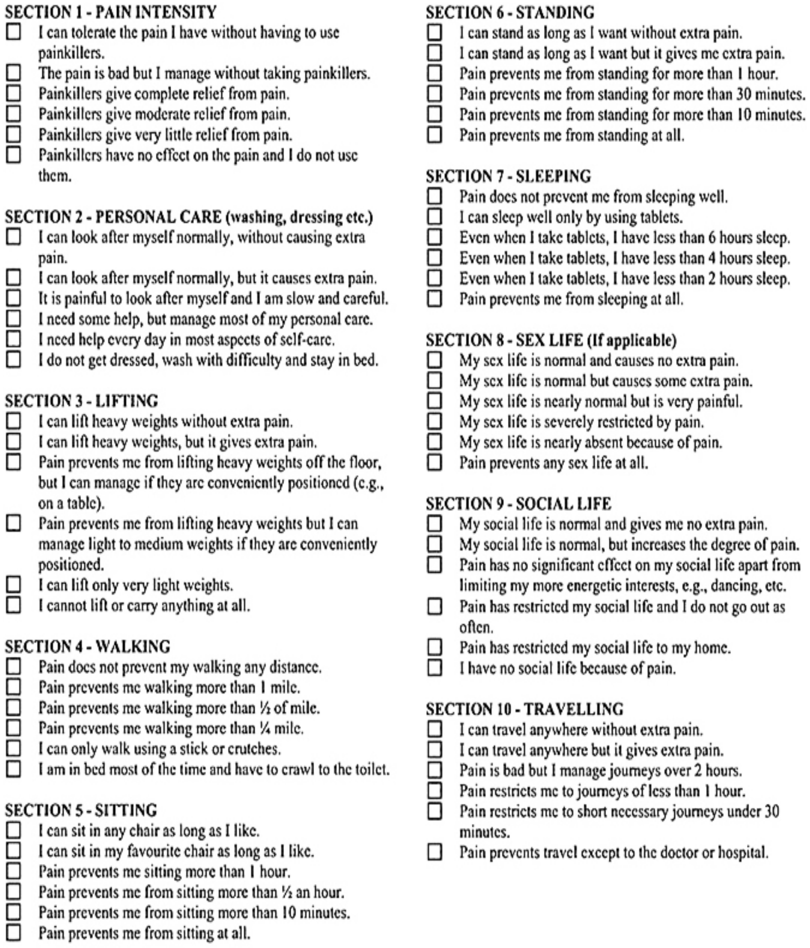
Morning Stiffness	☐	☐	☐	☐	☐
Stiffness occuring during the day	☐	☐	☐	☐	☐

Level of difficulty performing the following functions, on average, during the last 48 hours:

	None	Slight	Moderate	Severe	Extreme
Descending stairs	☐	☐	☐	☐	☐
Ascending stairs	☐	☐	☐	☐	☐
Rising from sitting	☐	☐	☐	☐	☐
Standing	☐	☐	☐	☐	☐
Bending to the floor	☐	☐	☐	☐	☐
Walking on flat	☐	☐	☐	☐	☐
Getting in/out of a car	☐	☐	☐	☐	☐
Going shopping	☐	☐	☐	☐	☐
Putting on socks	☐	☐	☐	☐	☐
Rising from bed	☐	☐	☐	☐	☐
Taking of socks	☐	☐	☐	☐	☐
Lying in bed	☐	☐	☐	☐	☐
Getting in/out of bath	☐	☐	☐	☐	☐
Sitting	☐	☐	☐	☐	☐
Getting on/off toilet	☐	☐	☐	☐	☐
Performing heavy domestic duties	☐	☐	☐	☐	☐
Performing light domestic duties	☐	☐	☐	☐	☐

The WOMAC parameters are:
0 – none, 1 – slight, 2 – moderate, 3 – severe, 4 – extreme.
The index is out of a total of 96 possible points, with 0 being the best and 96 being the worst

Figure 18. The Western Ontario and McMaster Universities Arthritis Index (WOMAC) questionnaire



SECTION 1 - PAIN INTENSITY
☐ I can tolerate the pain I have without having to use painkillers.
☐ The pain is bad but I manage without taking painkillers.
☐ Painkillers give complete relief from pain.
☐ Painkillers give moderate relief from pain.
☐ Painkillers give very little relief from pain.
☐ Painkillers have no effect on the pain and I do not use them.

SECTION 2 - PERSONAL CARE (washing, dressing etc.)
☐ I can look after myself normally, without causing extra pain.
☐ I can look after myself normally, but it causes extra pain.
☐ It is painful to look after myself and I am slow and careful.
☐ I need some help, but manage most of my personal care.
☐ I need help every day in most aspects of self-care.
☐ I do not get dressed, wash with difficulty and stay in bed.

SECTION 3 - LIFTING
☐ I can lift heavy weights without extra pain.
☐ I can lift heavy weights, but it gives extra pain.
☐ Pain prevents me from lifting heavy weights off the floor, but I can manage if they are conveniently positioned (e.g., on a table).
☐ Pain prevents me from lifting heavy weights but I can manage light to medium weights if they are conveniently positioned.
☐ I can lift only very light weights.
☐ I cannot lift or carry anything at all.

SECTION 4 - WALKING
☐ Pain does not prevent my walking any distance.
☐ Pain prevents me walking more than 1 mile.
☐ Pain prevents me walking more than ½ of mile.
☐ Pain prevents me walking more than ¼ mile.
☐ I can only walk using a stick or crutches.
☐ I am in bed most of the time and have to crawl to the toilet.

SECTION 5 - SITTING
☐ I can sit in any chair as long as I like.
☐ I can sit in my favourite chair as long as I like.
☐ Pain prevents me sitting more than 1 hour.
☐ Pain prevents me from sitting more than ½ an hour.
☐ Pain prevents me from sitting more than 10 minutes.
☐ Pain prevents me from sitting at all.

SECTION 6 - STANDING
☐ I can stand as long as I want without extra pain.
☐ I can stand as long as I want but it gives me extra pain.
☐ Pain prevents me from standing for more than 1 hour.
☐ Pain prevents me from standing for more than 30 minutes.
☐ Pain prevents me from standing for more than 10 minutes.
☐ Pain prevents me from standing at all.

SECTION 7 - SLEEPING
☐ Pain does not prevent me from sleeping well.
☐ I can sleep well only by using tablets.
☐ Even when I take tablets, I have less than 6 hours sleep.
☐ Even when I take tablets, I have less than 4 hours sleep.
☐ Even when I take tablets, I have less than 2 hours sleep.
☐ Pain prevents me from sleeping at all.

SECTION 8 - SEX LIFE (If applicable)
☐ My sex life is normal and causes no extra pain.
☐ My sex life is normal but causes some extra pain.
☐ My sex life is nearly normal but is very painful.
☐ My sex life is severely restricted by pain.
☐ My sex life is nearly absent because of pain.
☐ Pain prevents any sex life at all.

SECTION 9 - SOCIAL LIFE
☐ My social life is normal and gives me no extra pain.
☐ My social life is normal, but increases the degree of pain.
☐ Pain has no significant effect on my social life apart from limiting my more energetic interests, e.g., dancing, etc.
☐ Pain has restricted my social life and I do not go out as often.
☐ Pain has restricted my social life to my home.
☐ I have no social life because of pain.

SECTION 10 - TRAVELLING
☐ I can travel anywhere without extra pain.
☐ I can travel anywhere but it gives extra pain.
☐ Pain is bad but I manage journeys over 2 hours.
☐ Pain restricts me to journeys of less than 1 hour.
☐ Pain restricts me to short necessary journeys under 30 minutes.
☐ Pain prevents travel except to the doctor or hospital.

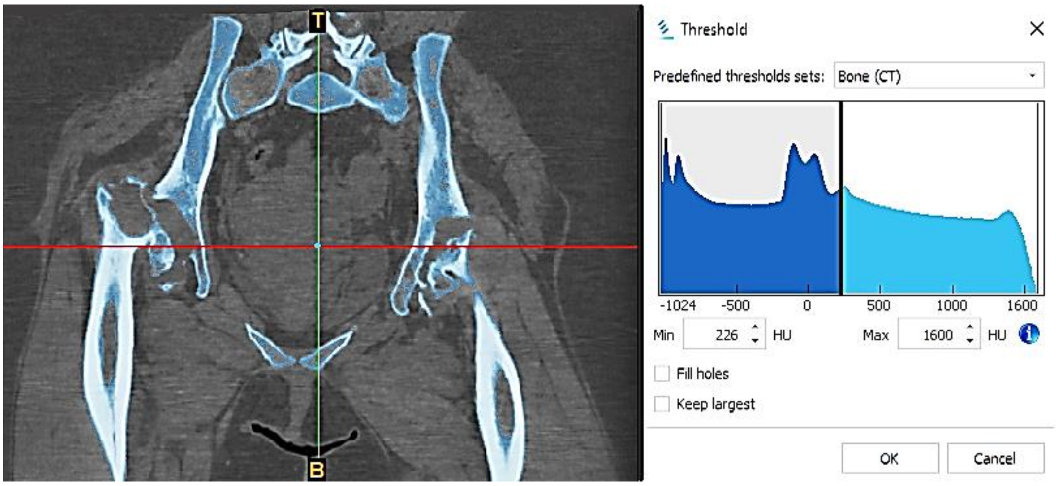
Figure 19. The Oswestry Disability Index (ODI) questionnaire

4.2 Mechanical study

4.2.1 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. (Figure 20)



Predefined thresholds sets: Bone (CT)

Min 226 HU

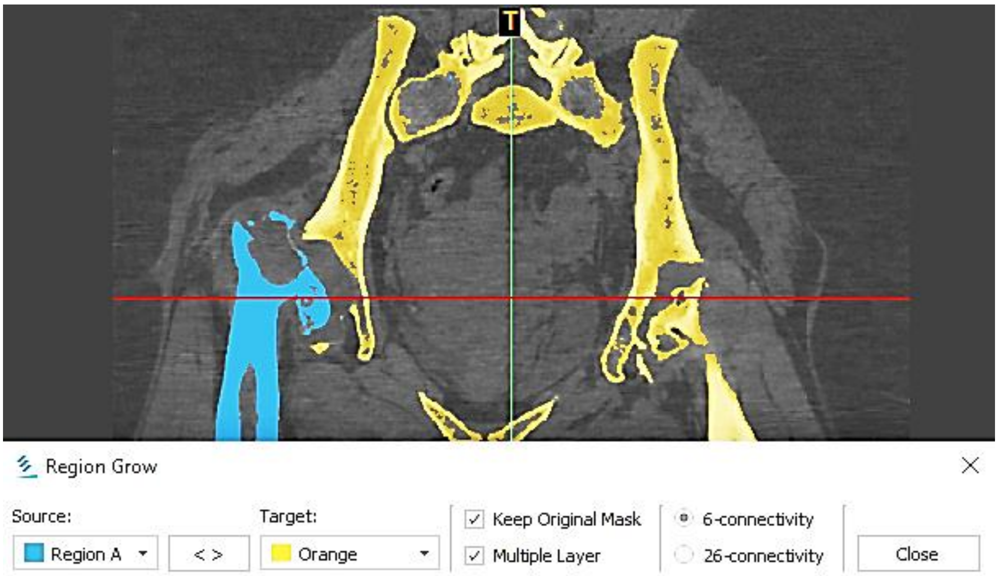
Max 1600 HU

☐ Fill holes

☐ Keep largest

Figure 20. Bone area selection

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. (Figure 21)



Source: Region A

Target: Orange

☑ Keep Original Mask

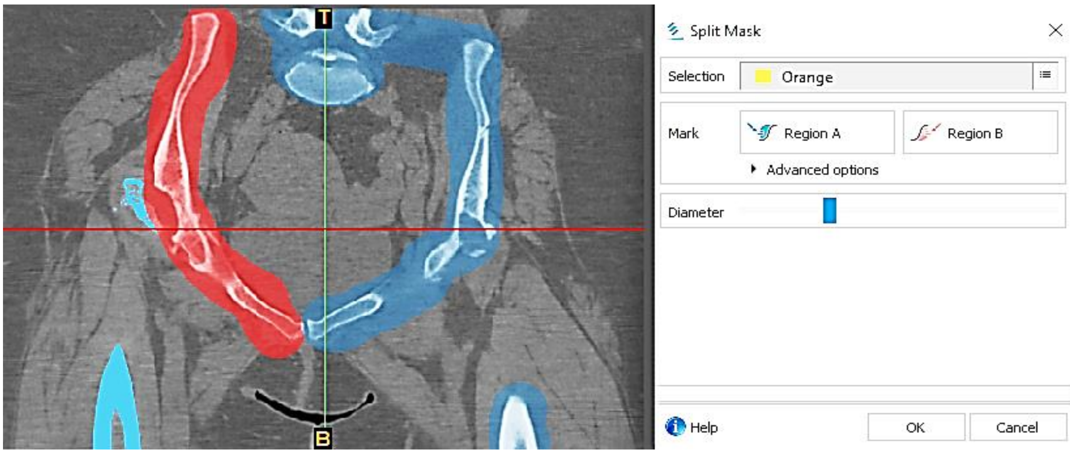
☑ Multiple Layer

● 6-connectivity

○ 26-connectivity

Figure 21. Deselecting the unconnected area

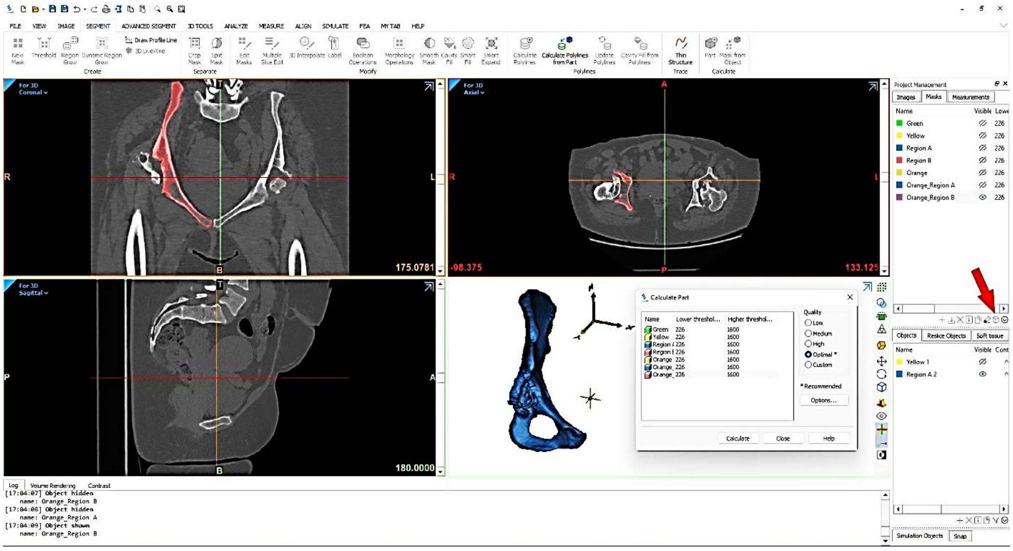
Step 3: The target hemipelvis is separated (red region) by the “Split Mask” tool. (Figure 22)



Selection: Orange

Figure 22. Selecting the target hemipelvis

Step 4: By clicking the cubic box as the red arrow showed below, the original 3D model is calculated (the "optimal quality" is selected). (Figure 23)



Name	Lower threshol...	Higher threshol...
Green	226	1600
Yellow	226	1600
Region A	226	1600
Region B	226	1600
Orange	226	1600
Orange_	226	1600
Orange_	226	1600

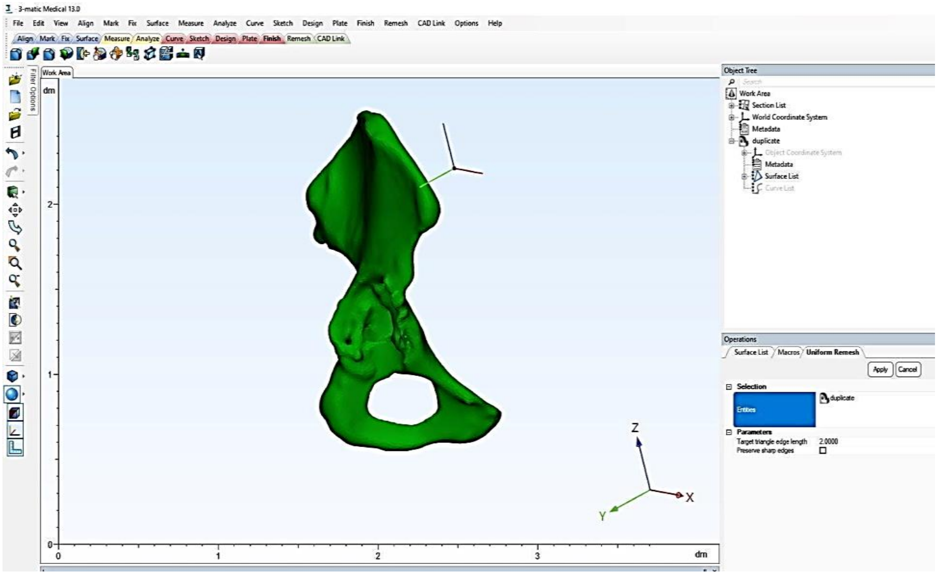
Quality
○ Low
○ Medium
○ High
● Optimal *
○ Custom

*Recommended

```
[17:04:07] Object hidden
    name: Orange_Region B
[17:04:08] Object hidden
    name: Orange_Region A
[17:04:09] Object shown
    name: Orange_Region B
```

Figure 23. Calculating the 3D model

Step 5: Further smoothing, polishing, remeshing the model is done in 3-Matic Medical software. (Figure 24)



Selection
Entities: duplicate

Parameters
Target triangle edge length 2.0000
Preserve sharp edges ☐

Figure 24. Further optimizing the model

4.2.2 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) (Figures 25, 26, 27). 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.

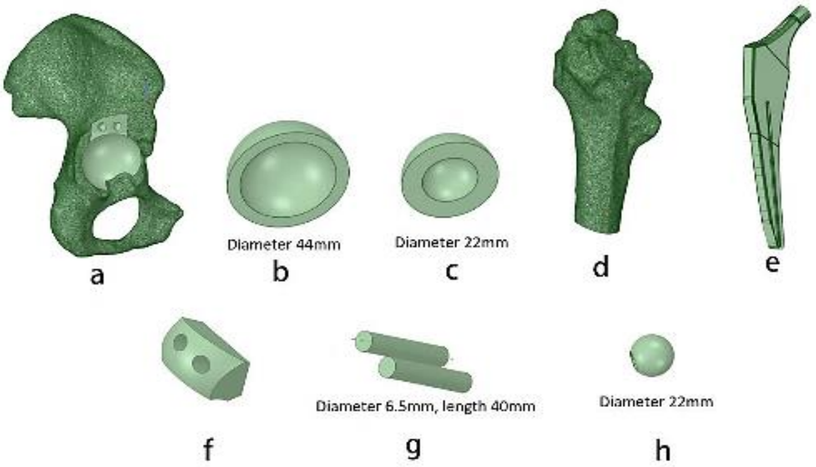
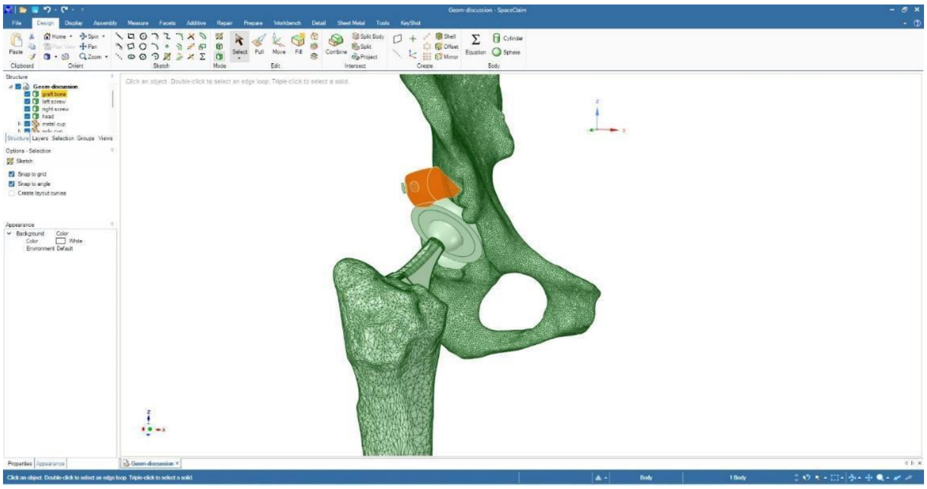


Figure 25. Main components and parameters for the 3D models. (a) solid hip model after subtraction by the metal cup, graft bone and two screws; (b) metal cup with inner diameter of 44 mm; (c) liner with inner diameter of 22 mm; (d) proximal femur solid model; (e) stem; (f) bone graft model after subtraction by the two screws; (g) simplified screw model; (h) 22 mm-diameter femoral head

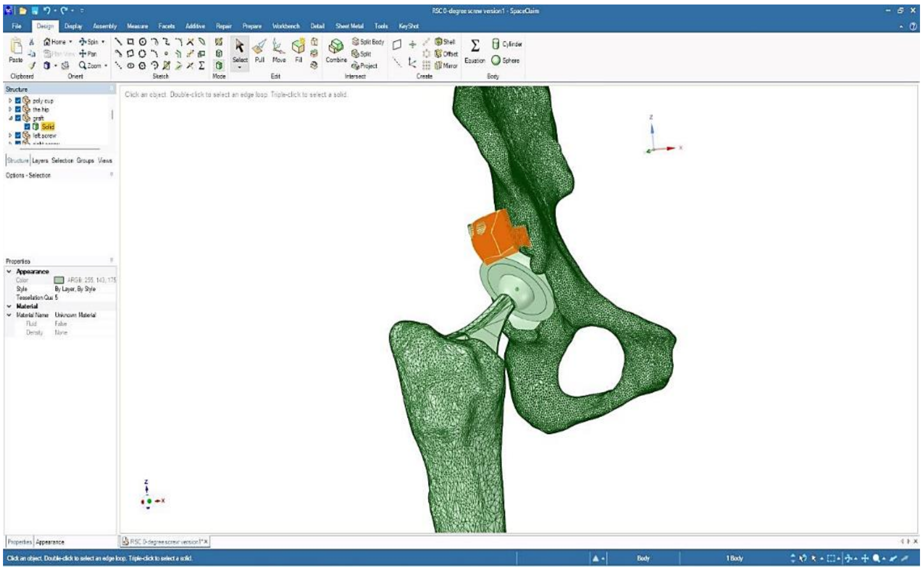


☑ Snap to grid
☑ Snap to angle
☐ Create layout curves

Background Color
Color White
Environment Default

Click an object. Double-click to select an edge loop. Triple-click to select a solid.

Figure 26. A 3D model of the BBG technique in SpaceClaim, the orange color represents the bulk shaped bone graft



Appearance
Color ARGB: 255, 143, 175
Style By Layer, By Style
Tesselation Qu: 5
Material
Material Name Unknown Material
Fluid False
Density None

Click an object. Double-click to select an edge loop. Triple-click to select a solid.

Figure 27. A 3D model of the RSC technique in SpaceClaim, the orange color represents the shape of the "L-shaped" graft

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 mm² vs. 674.1 mm²) (Figure 28).

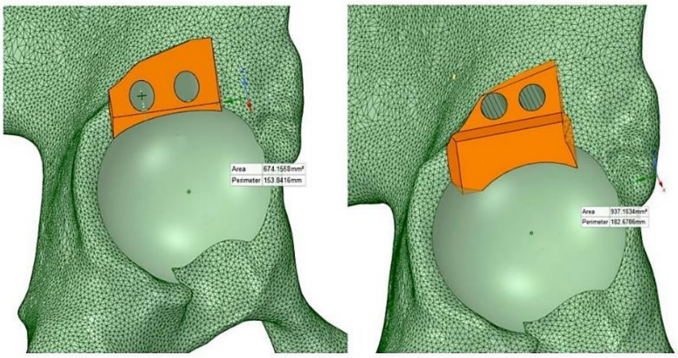


Figure 28. Graft-host contact bone areas of the bulk bone technique (left) and the roof step cut technique (right)

4.2.3 Finite element analysis (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[58], 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 (Figure 29). The analysis was based on the highest load experienced during jogging, which was set to 3000 N according to the publication[59]. 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 (Figure 30).

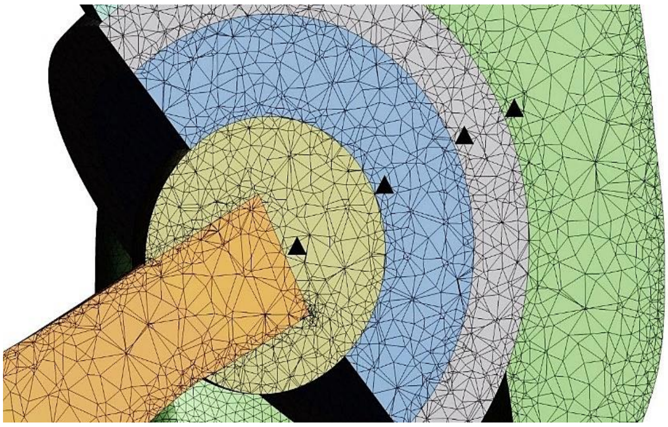


Figure 29. Mesh control in Ansys to ensure the contact mesh between the components are matched, black triangles indicate at all contacts matched meshes are created

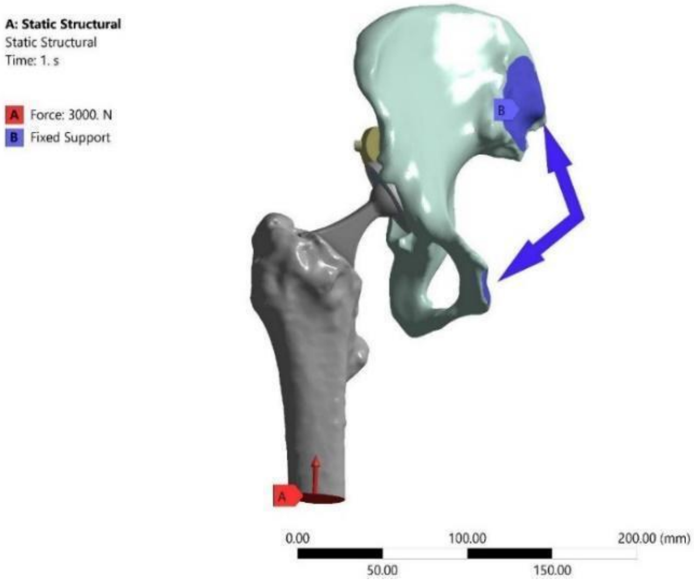


Figure 30. Actual simulating model in Ansys, the red arrow indicates the applied load, the blue arrows indicate the fixed area (the sacroiliac joint and pubic symphysis)

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 (Figure 31).

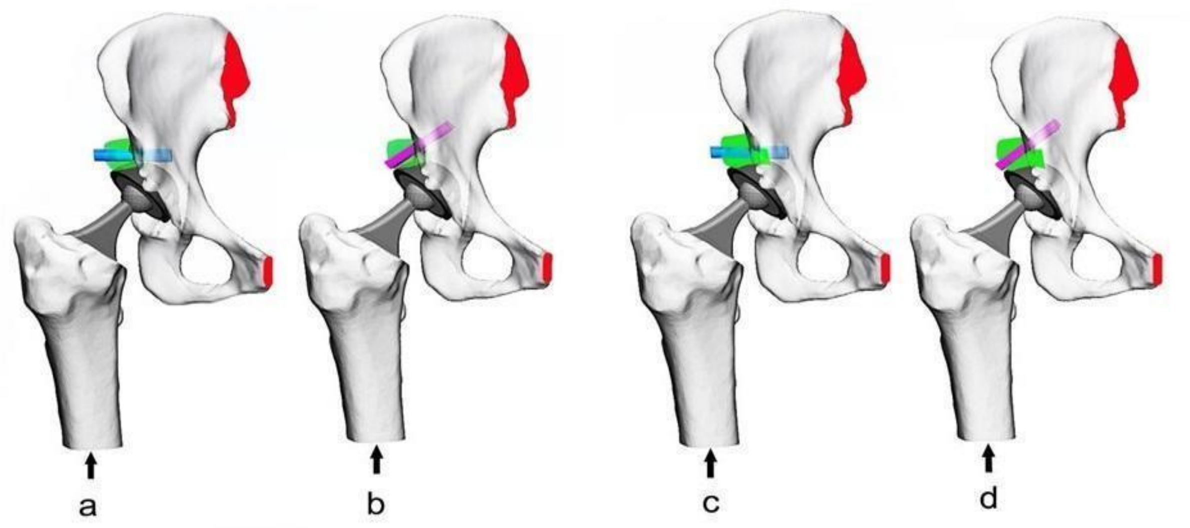


Figure 31. Harris BBG and RSC FEA models of total hip arthroplasty (THA) . (a) Harris method with two screws inserted at 0 degree (abbreviated as Harris0); (b) Harris method with two screws inserted at 45 degree (Harris45); (c) RSC technique with two screws inserted at 0 degree (RSC0); (d) RSC technique with two screws inserted at 45 degree (RSC45). The red region represents the fixed constraints surface in the FEA models, and the arrowheads indicate the applied force which is perpendicular to the distal femur surface.

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 (Figure 32).

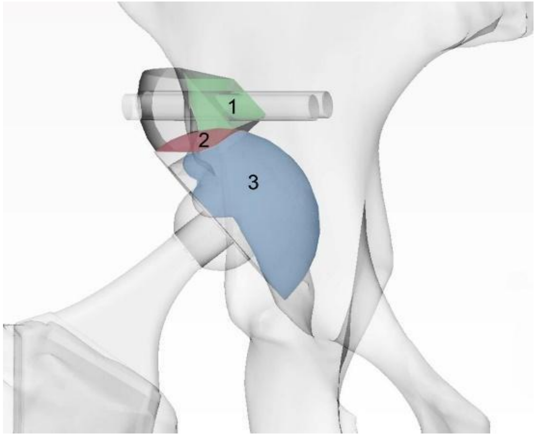


Figure 32. Contact surfaces for analyzing pressure and sliding distance. 1: bone graft-acetabulum surface; 2: bone graft-metal cup surface; 3: metal cup-acetabulum surface

5. Results

5.1 Clinical study

5.1.1 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.

5.1.2 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. Figure 33 depicts the long-term graft remodeling process at different time points in a single case.

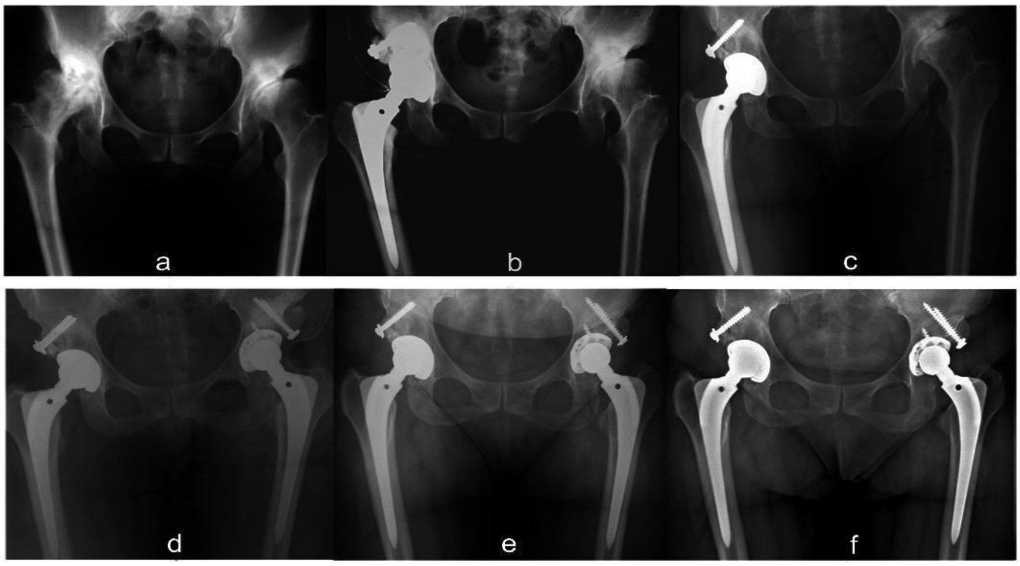


Figure 33. Female, 48 years old, with Hartofilakidis type B hip dysplasia. (a) Preoperative image; (b) Immediate X-ray after surgery; (c) Two years post-surgery; (d) Right hip: three-year control, left hip: immediate postoperative; (e) Right hip: five-year follow-up, left hip: two years post-surgery; (f) Right hip: eight-year follow-up, left hip: five years post-surgery. Both grafts have fully integrated with the host bone.

5.1.3 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 (Figure 34a), and statistically there was a significant difference between the timepoints 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) (Figure 34b). After the surgery, bone graft showed gradual increase of activity, at 12 months it became almost the same as the reference site. Figure 35 illustrates the scintigraphy changes observed in one patient after the surgery at different follow-up timepoints.

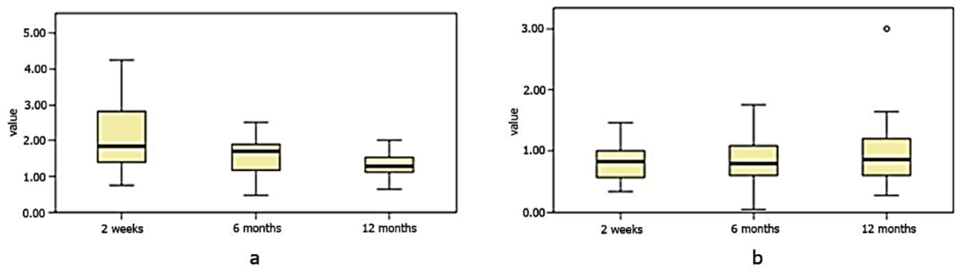


Figure 34. Comparison of whole-body planar scan (a), (H=9.129, P=0.01) and SPECT (b), (H=0.189, P=0.910) between the graft and reference at three checkup timepoints using the Independent-Sample Kruskal-Wallis test. SPECT: Single-photon emission tomography.

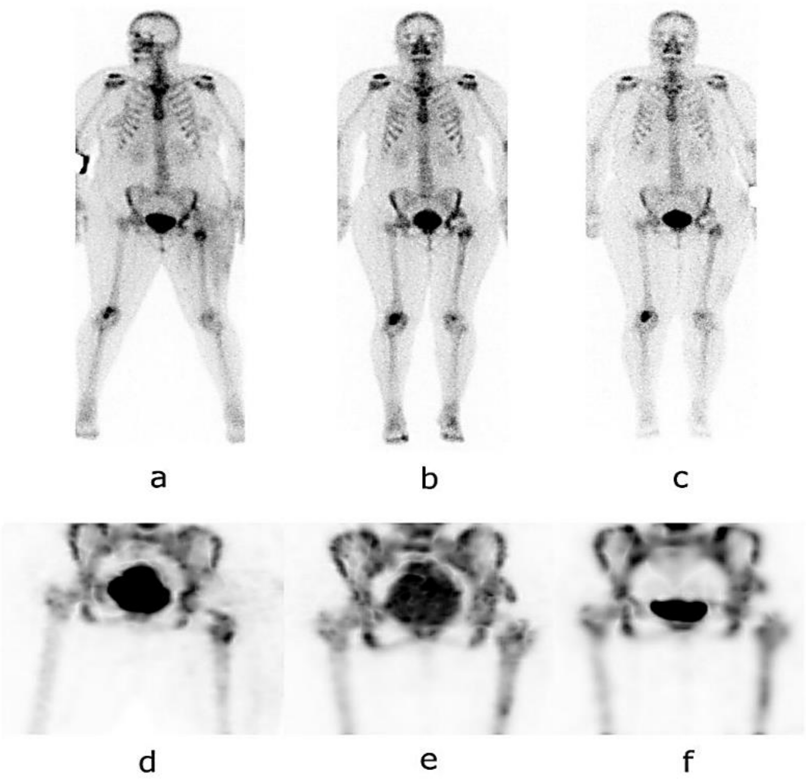


Figure 35. Post-surgery scintigraphy exam. (a-c) Whole-body planar scintigraphy at three checkup timepoints showed a gradual decrease in signal over time; (d-f) SPECT MIP of the graft at three checkup timepoints showed that the signal in the left hip graft area gradually increased and in the end presented almost the same number of signals as the reference side. SPECT: Single-photon emission tomography; MIP: Maximum intensity projection.

5.1.4 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, $P < 0.05$). Figure 36 illustrates the average changes in both scores over time. 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.

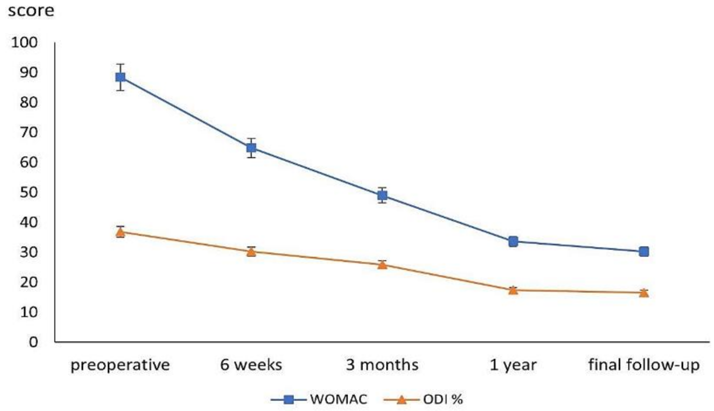


Figure 36. The preoperative and post-surgery average WOMAC and ODI scores. WOMAC: McMaster Universities Arthritis Index; ODI: Oswestry Disability Index

5.2 FEA biomechanical study

5.2.1 Stress distribution and deformation analysis of the bone graft

The von Mises stress distribution and total deformation of the grafts is displayed in Figure 37 (from the front and back views, respectively). 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 generates 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.

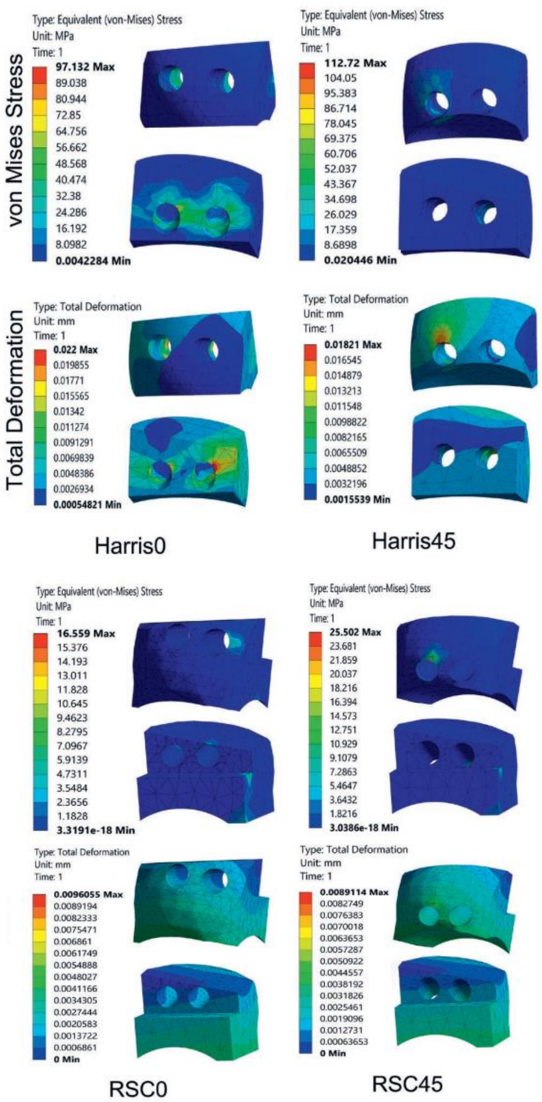


Figure 37. The distribution of Von Mises stress and total deformation of the grafts from the front view (1st, 3rd, 5th, 7th rows) and back view (2nd, 4th, 6th, 8th rows). Each column corresponds to one of the following models: Harris0, Harris45, RSC0, and RSC45.

5.2.2 Stress distribution and deformation analysis 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 the 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 (Figure 38).

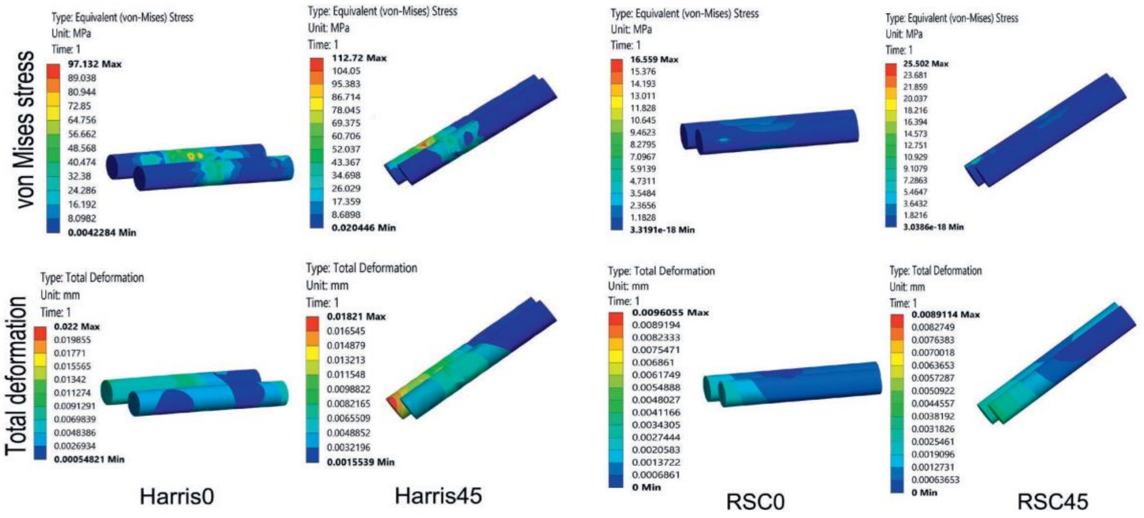


Figure 38. The stress distribution and total deformation analysis of the screws are analyzed in the models of Harris0, Harris45, RSC0 and RSC45.

5.2.3 Pressure and sliding distance analysis

Figures 39 and Figure 40 display the differences in pressure distribution and sliding distance across the four models. Three contact areas were analyzed: the graft-host bone contact (first row), the graft-metal cup contact (second row), the metal cup-acetabulum contact (third row) .

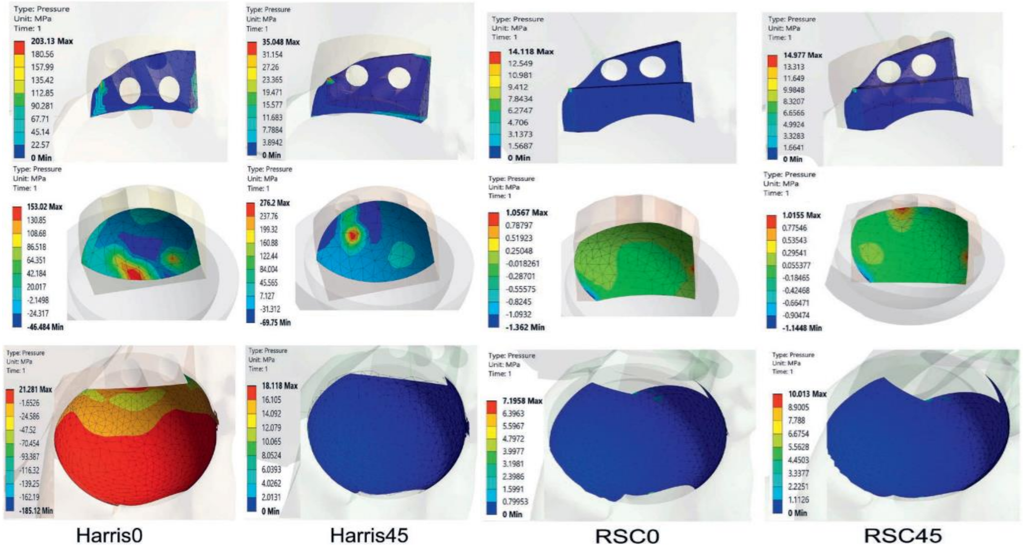


Figure 39. The pressure distribution analysis at the contacts between the components in the models of Harris0, Harris45, RSC0 and RSC45.

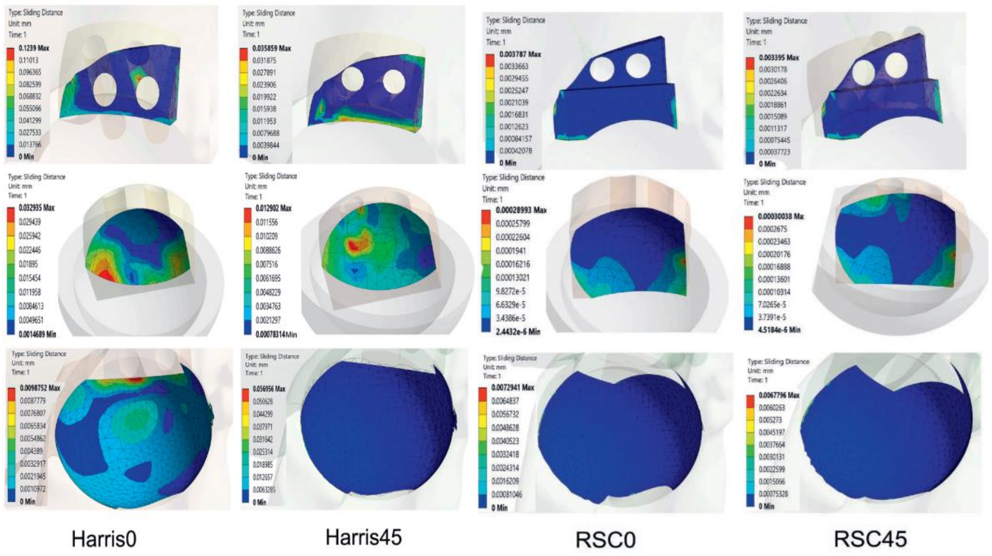


Figure 40. The sliding distance analysis at the contacts between the components in the models of Harris0, Harris45, RSC0 and RSC45.

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, Figure 41). 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.

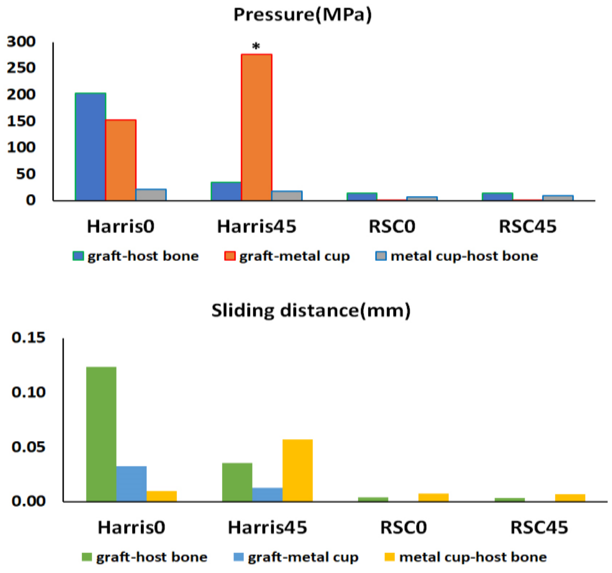


Figure 41. The pressure and sliding distance analysis at the contacts between the components, * indicates significant difference

6. Discussion

Developmental dysplasia of the hip (DDH) refers to the gradual severity of hip dislocation as the individual grows and develops. The femoral head gradually deforms and moves out of its normal position, and the shallow acetabulum cannot fully cover it. The normal force-bearing mechanism of the hip joint is disturbed, resulting in uneven force on the joint surface, and then the cartilage tissue is destroyed, which accelerates the occurrence of hip osteoarthritis. Clinically, patients could present symptoms such as limping, pain, and limited movement. As it could happen at a relatively young age, the patient's life quality and social function could be significantly affected. Conservative therapy's effect is quite limited for adults with hip dysplasia. Most patients need surgery to get their symptoms relieved. So far, many techniques have been reported in the literature[60]. The basic concept is to increase the coverage rate for the acetabular cup, either by adding a bone graft or an implant at the defective zone of the acetabulum, or by reaming the secondary pseudoacetabulum to achieve an HHC. Theoretically, the original hip rotational center has more advantages compared to other cup positions. However, the clinical outcome depends on lots of other influencing factors as well, such as the subjective factors of the surgeon, age of the patient, BW, living activity, bone quality, cement or cementless prosthesis, etc. What's more, as most patients undergo the surgery at a relatively younger age, attention should also be raised for the future revision possibilities. Therefore, clinical decisions sometimes could be quite challenging.

One of the purposes of the study is to introduce the RSC technique for the dysplastic acetabulum reestablishment which is developed in our department. Following up the patients at different time points, we planned to explore the surgery's effect on the clinical outcome. By 3D modeling and FEA, we arranged to compare the RSC's mechanical characteristics with the BBG technique. The clinical results showed that the RSC technique allows for simple and effective reconstruction of the acetabulum during surgery, with no obvious components loosening sign and good incorporation of the bone graft in the short-term after the surgery. The patients' mobility and functional recovery were also satisfactory. The mechanical analysis demonstrated that, compared to the BBG technique, the RSC technique showed more advantages. The stress distribution and deformation in the graft and screws were significantly reduced. On the contact surfaces of each component the pressure and sliding distance were also significantly decreased. Additionally, the screw insertion angle correlated with the location of highest stress and most pronounced deformation.

As previously mentioned, various techniques for THA in dysplastic cases have been reported in the literature, with outcomes varying significantly. Tsukada[61] described a bulk bone autografting technique that preserves the integrity of the cortical bone at the contact surface between the acetabulum and the femoral head. 22 dysplastic hip joints with around 8 years of follow-up time showed 100% survival rates for the uncemented cups and the function score significantly improved. The eccentric polyethylene wear rate was 36.4%, and the complete trabecular reorientation (the graft's trabecular structure matched the acetabular dome) rate was 68.2%. In a similar BBG approach, Delimar et al.[31] found that for hip dysplasia cases the overall stability of the cemented THA was poor, regardless of whether autologous or allogeneic bone was used. In the autograft group, 25% of cases were unstable after 4 years, increasing to 50% after 8 years. In contrast, the allograft group exhibited 25% instability after just 2 years and 50% after 5 years. Allografts demonstrated a failure rate twice as fast as autografts. Kenichi et al.[32] reported BBG technique with cemented cups, the grafts were categorized as being L shape, Wall and D shape types. 101 dysplastic hips were followed up to 11 years, the authors concluded that all grafts successfully achieved optimal trabecular bone structure match, and no revision surgery was required due to complications. It is worth mentioning that they applied the bone chips produced during the reaming process to the surface of the grafted bone and then secured it with screws.

Above mentioned studies used BBG from the femoral head to reestablish the acetabulum. There are also some other techniques we have summarized in the introduction part, of which the sample size was mostly limited[40, 41, 62, 63]. BBG is preferred because it is easier to perform and usually could achieve good cup coverage. The reasons behind the variety of reported results from the literature we believe include the following aspects: (1) Study subjects' diversity. Factors like patients' age, body mass index (BMI), bone quality, activity level, rehabilitation, nutrition, systematic/chronic disease, medicine and so on could all affect the outcome. Different studies used different inclusion criteria, different sample sizes and subjects with different clinical characteristics. (2) Technique difference. Although most studies used BBG from the femoral head. Very few reporters described the details of the graft. From our experiences, it is not always easy to sculpt from the femoral head due to the deformation and subchondral cysts. Some authors reamed the acetabulum first, then sculpted the bone graft with a size similar to the defect area and then fixed the graft with the screws[64]. While some authors reamed the original acetabulum and graft together to match with the metal cup in diameter[61]. About the contact aspect between the graft and the acetabulum, it can be cancellous bone contacts with cancellous bone, or cortical bone contacts with cancellous bone, or like in the study of Kenichi et al.[32], they placed the bone chip from the acetabulum reaming into the contact area. Choices about cemented or cementless cups, primary or high hip center are also important factors directly related to the final result. (3) Follow-up evaluation difference. Most studies did not show the details of postoperative rehabilitation. Different standards were applied to evaluate the prosthesis components stability, loosening and graft incorporation. Different questionnaires were used to evaluate the patients' function recovery and/or quality of life. They were evaluated at different postoperative time points. All of these perioperative factors cause the discrepancies in the results of the different studies. No doubt, there are factors beyond our control. But we still believe the RSC technique has some details that could favor the clinical outcome.

Benefits of the RSC technique

(1) Larger cancellous bone-cancellous bone contact

The "L-shaped" graft has a larger contact area between the graft and the acetabulum compared to normal BBG. We did not measure it during the surgery, but from the 3D models it showed the ratio of the contact area in both techniques was 1.5:1. Oscillating saw was used to prepare the host bone surface, expose the cancellous bone surface and also sculpt it into a step-like shape to perfectly fit the graft bone. So, finally a pattern-matched cancellous bone with cancellous bone contact was created.

Cancellous bones play a very important role in promoting the formation of new bones. On the one hand, various growth factors including osteoblasts are mainly distributed in the cancellous bone. On the other hand, the scaffold and porous structure of the cancellous bone itself provide the necessary structural basis for cell metabolism, distribution of new blood vessels, and transportation of nutrients[65, 66]. According to the literature, the postoperative healing process includes bleeding, necrosis of tissue cells, and later inflammatory reactions[67]. Under adaptive conditions, fibrovascular tissue gradually infiltrates into the cancellous bone of the graft to revascularize, providing a nutritional metabolic basis for the regeneration of bone tissue, while also supplying blood to the cortical bone through vascular channels[68]. Larger cancellous bone contacts provide a fundamental platform for bone regeneration and incorporation. In our study, postoperative X-ray exams at different time points showed that there was no loosening at 12 months after the surgery and until the last follow-up, 3 cases had osteolysis around the metal cup. Bone scintigraphy exam was also performed at postoperative follow-up to evaluate the graft's viability.

Bone scintigraphy proved useful for evaluating graft vascularity and viability in bone grafts, not only in the cancellous area, but also for the cortical part. Diffuse activity accumulation in the graft, similar to normal bone tissue, indicates successful graft incorporation[69-73]. Three-phase bone scintigraphy can accurately assess the metabolism and vascular distribution of the area of interest. In a positive scan, increased signal accumulation indicates active bone metabolism and good vascular reconstruction. In contrast, a negative scan shows minimal accumulation of active signals, suggesting a poor prognosis for the transplanted bone[74]. Bone metabolism around the implant could also be evaluated by scintigraphy, showing the dynamic changes during osseointegration. During SPECT, 3D images could be reconstructed according to the radiopharmaceutical distribution in the target area. Schliephake[75] and Berding[76] evaluated the bone healing process of autologous grafts in grossly atrophic edentulous jaws in conjunction with delayed placement of endosseous implants using SPECT. They declared that bone scintigraphic imaging could be useful for accessing tissue and cellular response and viability of autografts. Lauer et al.[77] used a microvascular bone graft for mandibular reconstruction, with graft viability assessed through bone scintigraphy at both the early stage (within 2 weeks after surgery) and the late stage (11 months postoperatively). The ROIs ratio of the graft and the background indicated that, at the early stage after surgery, there was an accumulation of activity signals, suggesting the success of the surgery.

In our study, we used planar whole body images and SPECT 3D images for the analysis. ROIs drawn on 3D images are more precise. From the detector's view, all counts can be accumulated, including those from radiopharmaceuticals in the skin, muscles, and bones. We chose the time point of two weeks after the surgery because we wanted to avoid the soft tissue oedema effect. In the study not all patients completed the scintigraphy exam. However, with the results of the included 23 cases, it consistently showed that along with the postoperative time, the ROI count activity ratio of the whole body gradually decreased and the values of the graft SPECT gradually increased, indicating the good bone graft incorporation.

(2) Autograft

Bone grafts are the second most commonly transplanted tissue after blood. It has been reported that when the bone defect area exceeds 30% of the acetabulum, bone grafting or the use of additional support implants should be considered[7]. Autografts, allografts, and bone graft substitutes can all be utilized for this purpose.

Autografts are considered the gold standard due to their minimal risk of immunological rejection and their significant advantages in promoting bone tissue regeneration and reconstruction, which are crucial for successful graft incorporation[78-80]. Cells from the graft have the potential to form new bones. Osteoblasts, which differentiate from osteoblast precursors, are the primary drivers of osteogenesis in the graft. Angiogenesis and the in-growth of mesenchymal stem cells (MSCs) are also essential in this process. Osteoconduction refers to the fact that the corresponding micro-scaffold and multi-porous structure of the graft provide a structural basis for the activity and metabolism of bone cells, which is conducive to the formation of new bone[81], acting as a bridge that facilitates graft-host bone incorporation. Osteoinduction refers to the aggregation and differentiation of stem cells in the bone graft under the action of various growth factors and osteoinductive factors[82]. These characteristics are unique to autografts, ensuring the most natural and effective incorporation of the graft with the host bone. However, autografts also present certain drawbacks, such as infection, hematoma and wound healing problems caused by improper bone harvesting surgery, and it is greatly affected by the patient's own factors. Some patients are not suitable for bone harvesting surgery or the bone tissue obtained is too limited to meet the needs of subsequent surgery[83].

Allografts offer a favorable alternative due to their convenience, abundance, and the absence of complications associated with bone harvest. However, the osteoinductive capacity of allografts is limited to some extent due to the influence of storage and processing methods. Freezing and freeze-drying are the two primary techniques used to extend the storage time and minimize the risk of disease transmission. Studies have shown that deep-frozen allografts incorporate much faster than freeze-dried allografts[84]. Nevertheless, both kinds of grafts have been shown to be feasible and reliable in practical applications. The results of mechanical research indicate that different processes may affect the biomechanical characteristics of bones. The torsional and bending strengths will decrease after freeze-drying, while simple freezing treatment will not have an adverse effect on characteristics such as compression, torsion and bending strength[85]. Radiation is also used clinically to sterilize allografts. However, studies have shown that when the radiation dose exceeds a certain limit (3 megarads), it can have a significant impact on torsional strength (reduced by 10-50%)[86]. Moreover, combining freeze-drying with irradiation over 3 megarads can significantly reduce the bearing capacity of the allograft[87]. Additional factors, such as the donor's age, sex, and physical characteristics, also have a significant impact on the biomechanical characteristics of allografts, survival of the bone graft, and the ultimate clinical prognosis.

(3) Primary rotation center

Based on Pauwels' theory, to maintain hip stability, the torques produced by BW are counteracted by the action of the abductor muscles. The moment arm of the abductor muscles could be affected by the position of the femoral head and the length of the femoral neck, lateral shift and the shortness could increase the overall hip load and cause it to more vertically press on the acetabular roof [88]. Erceg's theory further suggests that femoral head cranial migration could significantly generate more pressure on the acetabulum[89].

In cases of hip dysplasia, there is ongoing debate about the choice of acetabulum reconstruction position between HHC and the primary rotational center. The HHC is often preferred due to its simplicity in surgical execution. The acetabular cup could be better covered without extra support and the initial stability is usually satisfied. However, this approach may result in unfavorable biological stress, leading to a high rate of prosthetic interface wear and complications. From this perspective, some scholars recommend restoring the primary hip rotation center during surgery[90], although this is a more challenging procedure. In cases of DDH, the acetabulum is usually significantly malformed, appearing shallow and flat, with the formation of a false socket. There is often an increase in acetabular anteversion and inclination, and the center of hip rotation shifts upward and laterally. Additionally, osteophyte proliferation and changes to the acetabular walls are common. Numerous methods have been proposed to define the hip rotation center more accurately[91-94], and with the aid of computer-assisted technology and 3D printed life-size models, orthopedists can more quickly and precisely determine the rotational center. Restoring the original hip center helps compensate for the shortcomings of an HHC. This adjustment results in a more parallel rotational axis, increases the tension in the gluteus medius and minimus muscles, and aids in correcting Trendelenburg gait. Furthermore, it reduces the shear forces at the host bone-graft contact, promoting better bone incorporation.

Delp et al.[95] reported that the cranial movement of the cup could decrease 10% of the moment arm of adductor muscles and by 28% when placed in the superolateral position. Jerosch et al.[96] built up a simulating model based on cadaver specimens and also found that the abductor muscles became weakened when the hip center was positioned at a higher elevation. These findings suggest that putting the cup in a more inferior and medial position is biomechanically more favorable than superior and lateral position.

Clinically, the complication rate of HHC is very significant. In a study by Kelly et al.[97], 23 HHC THA hips were studied with an average 35 months follow-up, they found 5% of cup loosening and 25% of stem loosening. Similarly, Schutzer et al.[98] by following 56 joints for 40 months reported 6% of the acetabular loosening rate. Hendricks[99], in a long-term follow-up of 23 joints for an average of 16.8 years, found that 4.3% of joints required reimplantation due to acetabular loosening, while 28.2% required femoral reimplantation. Due to the ischial impingement, there is a higher risk of dislocation for a high hip rotational center. Therefore, given the increased risk of complications, a HHC is generally not the first choice.

In our study, the hip rotation center is evaluated before the surgery based on the anterior-posterior X-ray image. After the femoral head is cut during surgery, the primary hip joint center can usually be determined based on the surrounding anatomical features. From the frontal plane a line is drawn between the anterior superior iliac spine and the pubic symphysis, the rotation center is approximately 1.5±2.0 cm distal to the midpoint (Figure 42). This method also was agreed by some other reporters[94].

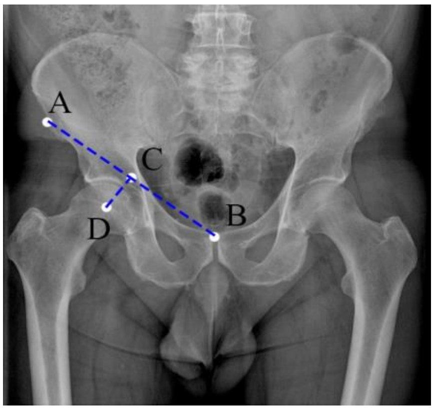


Figure 42. Location of primary hip center based on the anterior-posterior pelvic X-ray. A: anterior superior iliac spine, B: pubic symphysis, C: midpoint of AB, D: primary hip rotation center

(4) Cementless cup

The placement of cementless cups offers distinct advantages, particularly in terms of increasing the diameter of the acetabulum. This allows for the use of a larger metal cup and provides more flexibility in choosing a liner cup with appropriate thickness and femoral head of corresponding diameter. In primary THA, fixation methods include cemented, cementless, and hybrid approaches. For cemented implants, prosthesis stability is achieved through the chemical reaction of the polymethylmethacrylate solidifying, ultimately forming a strong mechanical interlock between cement and bone (Figure 43b,d). For cementless prostheses, stability at the beginning comes from the press-fit stability achieved by pure mechanical expansion, and the long-term satisfying outcome is achieved through bone regeneration and close connection with the microporous structure on the prosthesis surface (Figure 43a,c).

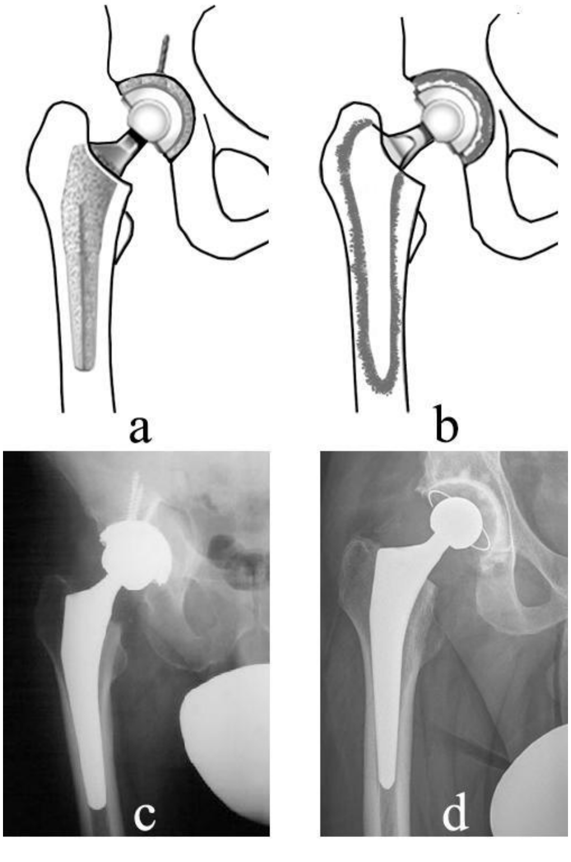


Figure 43. Diagram and X-ray of cementless (a,c) THA and cemented THA (b,d)

Clinically, the patient's age will have a certain impact on the choice of prosthesis. Bone cement fixation is more suitable for elderly patients with poor bone quality, while non-bone cement fixation is more suitable for younger patients with better bone quality. On the one hand, the long-term survival rate is better, and on the other hand, the difficulty of subsequent revision surgery needs to be taken into account. However, periprosthetic fractures tend to be more common with cementless fixation. Cemented cups are not considered the first choice because it is believed that during the insertion of the cemented cup into the acetabulum, a small amount of cement may inevitably be pressed into the space between the host bone and graft. This can hinder graft incorporation and lead to instability of the entire prosthesis. Additionally, cemented cups pose significant challenges in future revision surgeries, which are more likely to be required in younger patients with DDH. Surgeons must carefully consider the long-term implications of each fixation method and choose the most suitable option for each patient, keeping in mind the potential need for future revisions.

(5) Better fixing mechanism

FEA offers a cost-effective and efficient method for simulating and reproducing complex biomechanical behaviors in orthopedic research. Initially developed to address structural analysis problems in the fields of mechanics and aeronautical engineering, FEA has proven to be particularly well-suited for studying physiological systems, even when their complexities are significant. Today, FEA has become an essential tool in the orthopedic operation field, allowing surgeons to gain a deeper understanding of biomechanical changes following prosthesis or osteosynthesis implantation, as well as the biological responses of bone to these changes[100-103]. One of the additional benefits of FEA is its ability to predict stress distribution around implanted areas, helping to prevent complications due to improper positioning or fixation of the prosthesis. By simulating these processes, orthopedic surgeons can anticipate how implants will behave mechanically, especially in deformity correction cases. FEA provides more detailed and dynamic information about the forces and angles acting on the joint during movement, which can directly inform and improve clinical practice by offering reliable, evidence-based insights.

Normal body load transfer starts at the femoral head, then through the medial cortical bone of the neck to the lesser trochanter, and ultimately down the diaphyseal bone[104, 105]. It is well known that the forces acting on the greater trochanter during this process are mainly generated by the abductor muscles[106, 107]. Typically, the muscle strength exerted on the femoral head is 2.75 times the BW and in the double support phase or heel impact during walking, the femoral head can withstand force of about 4 times the BW[102].

Several studies have utilized FEA to investigate the load effects on the hip. Levine et al.[108] employed FEA to analyze the effect of trabecular metal (TM) augmentation for the roof defect of the acetabulum. Their findings indicated that TM augmentations offered structural stabilization and helped restore the hip's center of rotation. Yoshida et al.[109] developed a 3D dynamic FEA model of the hip to study stress distribution during daily activities. Their results indicated that contact forces are the greatest during the initial mid-stance phase, when a single leg supports the weight of the entire body. During this phase, patients loaded 81% of their BW on the hip joint when standing on one leg, and 238-390% of their BW during normal walking, with values reaching 500-600% during jogging. Jun Fu et al.[110] similarly set load values at 500 N (representing 100% BW during single-legged standing), 2000 N (4 times BW during normal walking), and 3000 N (6 times BW during jogging). Zhao et al.[111] explored the design of mortise-tenon joints using FEA to study their effects on the stability of bone grafts for acetabular defects. The mortise-tenon structure, inspired by ancient Chinese architecture, is a joint type that relies on interlocking components without the need for screws. Their results showed that this screw-free structure offered a broader stress distribution across the superior and medial parts of the acetabulum.

These studies highlight the utility of FEA in orthopedic applications, particularly in understanding and optimizing bone grafts, prosthesis designs, and joint mechanics under various loading conditions. Through this simulation technology, orthopedic surgeons can improve treatment outcomes by making better-informed decisions on implant positioning, fixation techniques, and the management of bone defects.

From the literature, we summarized the testing method. The analysis was conducted in jogging mode, reaching an equivalent of 3000N to demonstrate the maximum mechanical effects on the components. The biggest problem was the volume mesh material definition. There are reports defining the whole hip as cortical bone[112], therefore we decided to follow the steps. Given that the study aimed to compare the mechanical effects of the two techniques, and the same material definition method was used, the results can still be considered reliable. We have an idea to improve the result of the current methods. By the “shrink” function of the 3-Matic software, we could create a 2 mm thickness cortical bone layer, and the rest will be the cancellous bone. Then the material definition will not be a problem in Ansys software and the result could be more accurate. All in all, future study is needed to define the cortical and cancellous bone parameters separately to achieve results closer to reality.

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 reduced the 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.

7. Summary

The RSC technique was developed by the senior surgeon, Professor Zoltán Csernátony, in our department and has been used for over a decade on patients with hip dysplasia. Clinically, by postoperative X-ray, bone scintigraphy and function questionnaires, this technique showed satisfactory results. No obvious adverse clinical events occurred. However, it is necessary to extend the follow-up time and continue the study to obtain more compelling results. In this study, we also mechanically compared the RSC technique with the common BBG method. The aim was to explore whether the "L-shaped" graft and 45° fixing screws could generate favorable mechanical effects. Therefore, parameters like the stress distribution, deformation, pressure and sliding distance are primarily analyzed among the components and at the contact surfaces between them. The results showed that RSC technique indeed could help improve general stability. Even though the operation time will be longer to sculpt the graft and prepare the host bone area, we believe it's still necessary to perform this technique, especially if the patient undertakes the THA surgery at a relatively younger age. For those cases with highly deformed femoral heads or big subchondral cysts, "L-shaped" titanium or tantalum implants could have great values in the future market.

8. Bibliography

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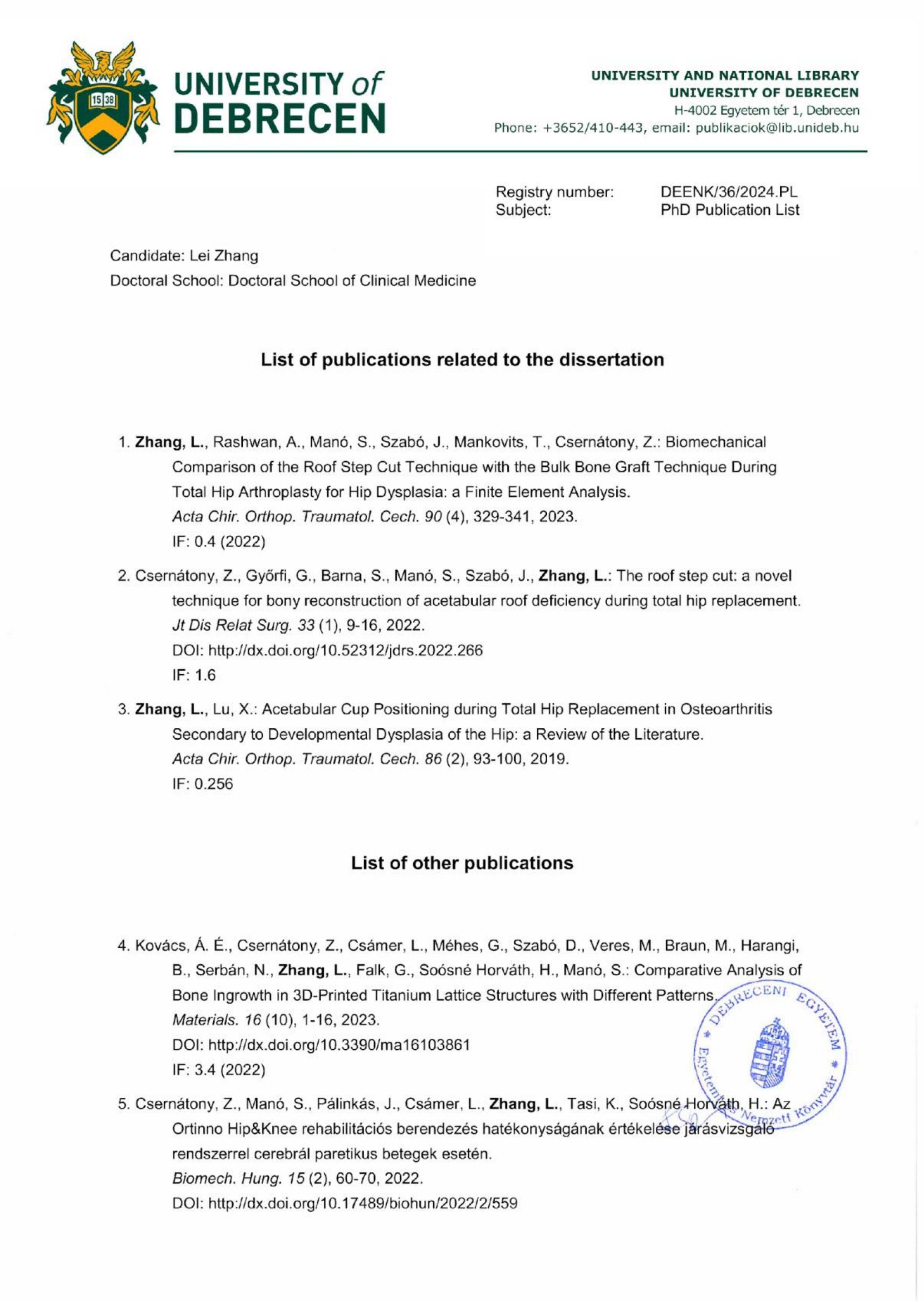
8.2 Authenticated list of Candidate's Publications



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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.
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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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5. Csernátony, Z., Manó, S., Pálinkás, J., Csámer, L., **Zhang, L.**, Tasi, K., Soósné Horváth, H.: Az Ortinno Hip&Knee rehabilitációs berendezés hatékonyságának értékelése járásvizsgáló rendszerrel cerebrál paretikus betegek esetén.
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6. Csernátony, Z., **Zhang, L.**, Takács, K., Csámer, L., Kovács, Á. É., Manó, S.: Metal implants and MRI: a mythbuster study.
   Glob. Imaging Insights. 6, 1-4, 2021.
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7. Csernátony, Z., Kovács, Á. É., Csámer, L., **Zhang, L.**, Manó, S.: Állatkísérleti modell kidolgozása rácsos mikroszerkezetű titán implantátumok értékelésére.
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8. Csernátony, Z., Győrfi, G., **Zhang, L.**: Case title: Roof Step Cut-A Novel Technique for Bony Reconstruction in Acetabular Roof Deficiency.
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    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

9. Keywords

Hip dysplasia
Total hip arthroplasty
Autograft
Acetabulum reconstruction
Primary rotation center
Scintigraphy
Finite element analysis
3D modeling
von Mises stress
Deformation
Mechanical stability
Sliding distance
Bulk bone graft

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11. Appendices