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ORIGINAL PAPER
PÙVODNÍ PRÁCE

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

Biomechanické porovnání techniky plastiky acetabula pomocí schodovitě opracovaného štěpu s technikou masivního kostního štěpu u TP kyčle po dysplazii: analýza konečných prvků

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ABSTRACT

PURPOSE OF THE STUDY

Different techniques have been reported to reconstruct the deficient acetabulum during total hip arthroplasty (THA). The purpose of this study was to compare the biomechanical features of the bulk bone graft (BBG) technique (Harris acetabular plasty) and the Roof Step Cut (RSC) technique using finite element analysis.

MATERIAL AND METHODS

Based on a female patient‘s dysplastic hip CT scan, 3D models were assembled according to the two techniques. For the Harris technique, an irregular BBG was sculpted from a solid sphere, while for the RSC technique, the graft was sculpted into a step-cut shape with a similar size. Each graft was fixed with two compression screws at two different angles (0° and 45°). Four finite element models were used to compare the von Mises stress distribution and total deformation of the grafts and the screws. The pressure and sliding distances of the contacts between the bone graft, metal cup and acetabular host bone were also analyzed.

RESULTS

For both of the bone grafts and the screws, compared to the Harris models, the maximum stress of the RSC models was significantly lower (16.56 MPa, 25.50 MPa vs 97.13 MPa, 112.72 MPa) and the total deformation was significantly smaller (0.0096 mm, 0.0089 mm vs 0.022 mm, 0.018 mm). 45° inserted screws generated higher stress at the end of the screws and on the outside of the bone graft. In case of 0° inserted screws, the maximum value was mainly located in the middle of the screws, inside the screw channel as well as at the contact area between the graft and the host bone. At all analyzed contacts, the RSC technique shows significantly lower pressure and sliding distances, irrelevant to the screw's insertion angle. In comparison, the model of BBG with 45° screws showed a significant sliding effect and higher contact pressure.

CONCLUSIONS

Compared with the BBG technique, the step-shaped graft of the RSC technique could significantly reduce the maximum stress and deformation of the graft and the screws, and decrease the pressure and sliding distance between the bone graft, metal cup and the acetabular host bone. The angle of screw placement affects the location of stress and deformation.

Key words: developmental dysplasia of the hip, total hip arthroplasty, acetabular reconstruction, bone graft, finite element analysis

INTRODUCTION

Total hip arthroplasty (THA) is still the leading solution for secondary osteoarthritis caused by developmental dysplasia of the hip (DDH). The goal and also the challenge is to achieve proper bone coverage and restore the rotational center of the hip. It is reported that the lateral part of the acetabular roof is essential for load transfer and the coverage rate should be more than 70% (13, 19). Since the dysplastic acetabulum is shallower and has a triangle-shaped hiatus in the inner superolateral aspect**,** extra augmentation is usually needed. As for the rotational center, on the one hand, Pauwels‘ and Marinko‘s theory proved that cranial and lateral shift of the femoral head could both increase the compressive force on the acetabulum (4, 17). On the other hand, the primary rotational center has distinct advantages over other cup positions in some respects, such as parallel rotational axis, decreased adductor muscle tension, more bone stock, etc. (23). These fac-

tors are all crucial to reestablish the biomechanics of the hip joint.

Compared to augmentation material like titanium or tantalum, the autologous graft sculpted from the femoral head is mostly used to reconstruct the dysplastic acetabulum, depending on the surgeon‘s view and the budget. In 1977, Harris firstly reported the acetabular plasty technique, the femoral head was used as a bone graft, attaching it to the acetabular wall to provide bone stock for reconstruction (6). Since then, this method has been constantly developed and evolved into a wide range of different techniques, for example, the iliac sliding graft technique, intraosseous structural graft technique, vascularized pedicle iliac crest graft technique and so on (7, 20, 21). The Roof Step Cut (RSC) technique was developed by our department and has been applied in hip dysplasia cases for more than ten years. The general concept is sculpting the femoral head into an step-shaped graft while preparing the host bone on the contact area into the shape similar to the staircase steps. Two compression screws at a 45-degree angle are used to fix the graft. A short and mid-term follow-up study has proved that this technique could provide enough coverage for the cup and assure proper primary stability (2).

Finite element analysis (FEA) has been widely used to solve many engineering problems related to structural analysis. Its applications in the orthopedic field include implant properties, bone-implant interface analysis, augmented material biomechanical study and so on (3, 12). However, a comparative study focusing on the bone graft shapes and the screws‘ insertion angles for THA of DDH cases is still missing. Therefore, this current study aims to establish an FEA model of THA surgery for hip dysplasia, in which acetabular roof was reconstructed by the Harris method or by the RSC method. The grafts were fixed by two screws in 0° and 45° direction separately. The stability and stress distribution of bone graft and the screws, the contacts' pressure and the sliding distances were analyzed.

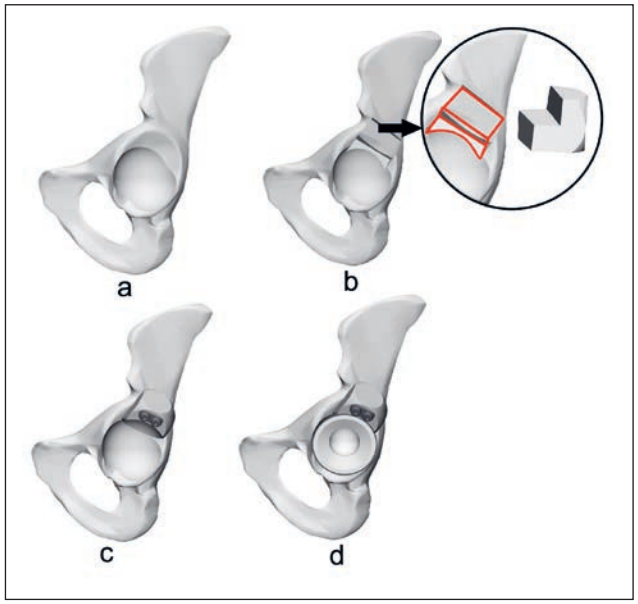


Fig. 1. The surgical procedure of the RSC technique; (a) acetabulum reaming; (b) making the step-shaped spongiotic host bone surface; (c) fixing the graft with compression screws at 45°; (d) inserting the uncemented cup in a press-fit way.

MATERIAL AND METHODS

Introduction of the RSC technique

Details of the procedure can be found in previous publication (2). In brief, a standard anterolateral approach is used for the surgery. After checking the primary acetabulum, the achievable reaming is usually performed with the smallest diameter reamer (Fig. 1a). A horizontal cut is made at the cranial wall of the acetabulum, which is supplemented by a vertical cortical refreshing cut at the lateral aspect of the ilium, resulting in a rectangular spongiotic host surface. Then the femoral head is sculpted to achieve a right-angled profile graft with a possibly preserved external cortical and spongiotic surface (Fig. 1b). After the graft is fitted onto the intra- and supra-acetabular bed, it is fixed temporarily by a Kirschner wire. The final fixation is carried out by inserting two compression screws with a 45° angle. By undermining the overhanging graft, a reliable contact is achieved with the cranial aspect of the cup (Fig. 1c). After rechecking with trial cups, an uncemented cup is finally inserted in a press-fit way (Fig. 1d).

Reconstruction of THA models based on two techniques

Based on the CT scan of a DDH patient (female, 47 yrs) from our department, the 3D model of the pelvis was restored using Mimics Research 21.0 (Materialise, Leuven, Belgium). After smoothing, polishing and other basic surface processing in 3-Matic (Materialise, Leuven, Belgium) 3D modeling software, a suitable hemipelvis 3D surface model (*STL) was exported. The patient had signed an informed consent for this research purpose. The study was conducted in accordance with the principle of the Declaration of Helsinki.

According to the actual size of the solid hip model, THA components were assembled using Ansys SpaceClaim software (2022 R2 version, Canonsburg, USA). The diameter of the acetabular cup was 44 mm. The cup inclination is 40° and the anteversion is 20°. A 22 mm ceramic femoral head and liner were “implanted”. In this study, two types of surgical techniques were compared: (1) BBG technique originated from Harris acetabular plasty; (2) RSC technique. In order to analyze the effect of the compression screws, for each technique, two screws of 40 mm length and 6.5 mm diameter were inserted at two different angles (0° and 45°) to fix the graft bone. Therefore, four models (abbreviated as Harris0, Harris45, RSC0 and RSC45) were reconstructed for the FEA analysis (Fig. 2).

The shape of the grafted bones is irregular. They were sculpted from a solid sphere, simulating the femoral head in real-life surgery. For the purpose of minimizing the error caused by the size, the size of the two kinds of grafts

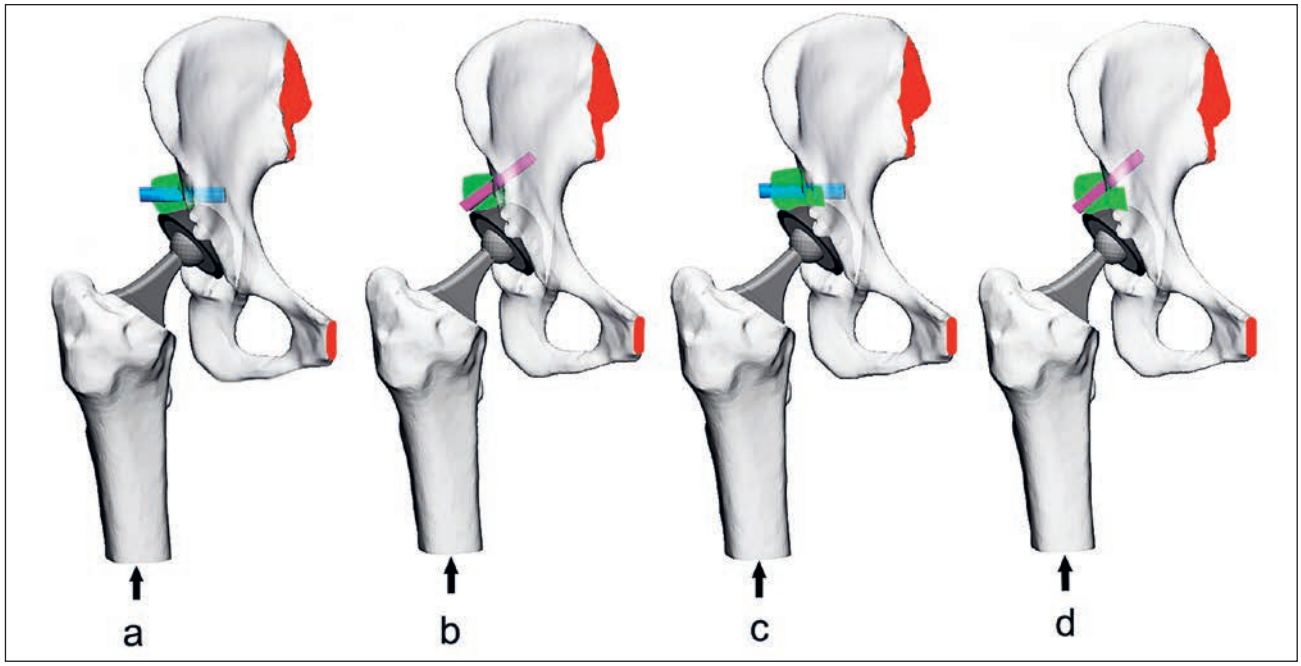


Fig. 2. FEA models of THA with loading conditions and components; (a) Harris BBG with two 0° inserted screws (abbreviated as Harris0); (b) Harris BBG with two 45° inserted screws (Harris45); (c) RSC step-shaped graft with two 0° inserted screws (RSC0); (d) RSC step-shaped graft with two 45° inserted screws (RSC45). The red areas indicate the fixed constraints of FEA models and the arrowheads indicate the force direction.

was kept almost consistent. The height, width and depth of the BBG were 11–19, 30 and 6–10 mm, respectively; those of the step-shaped bone graft were 15, 30 and 15 mm, respectively. The host bone area calculated by the software was 674.1 mm^2 for the BBG technique and 937.2 mm^2 for the RSC technique.

FEA analysis

The FEA simulation was performed using ANSYS Workbench software (2022 R2 version, Canonsburg, USA). Material properties applied to all parts of the model were set into ANSYS materials, as shown in Table 1 (3).

Table 1. Materials properties

Material	Young's modulus (MPa)	Poisson's ratio
Cortical bone	17300	0.265
Cancellous bone	400	0.200
Titanium	110600	0.326
Ceramic linear/femoral head	350000	0.220

The solid model was exported to Ansys Workbench where all geometries were identified and set to their matching materials. Mesh generation was executed with a general size of 3 mm and a fined mesh size of 0.8 mm on the areas of contacts. The element type was set to automatic (Solid 187), where a total number of 365738 elements and 626052 nodes were generated. Bonded contact type was chosen for all interconnections between most of the parts. Frictional contact with a friction coefficient of 0.2 was selected for any contact with a screw and with a coefficient of 0.1 between the femoral head and the socket. The analysis was set to be performed based on the highest load which takes place in the jogging mode and reaches an equivalent of 3000 N (1). The force was applied in a perpendicular direction to the bottom surface of the femur. Loads related to muscles around the hip joint were neglected in the study. The model was constrained as fixed at the sacroiliac joint and pubic symphysis.

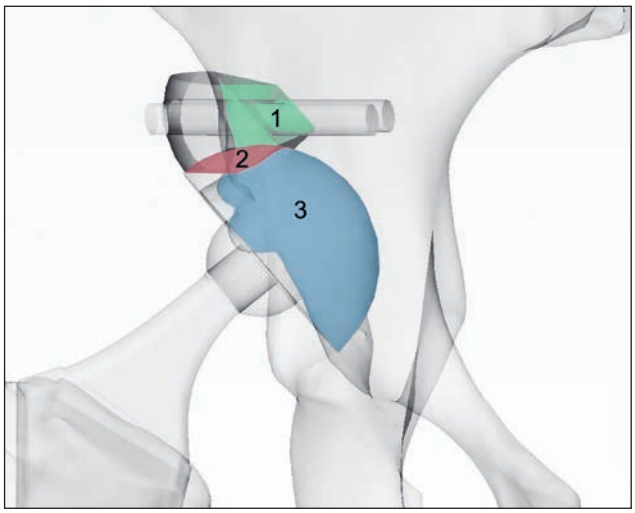


Fig. 3. Contact surfaces for the pressure and sliding distance analysis; (1) surface between the bone graft and the host bone; (2) surface between the bone graft and the metal cup; (3) surface between the metal cup and the acetabular host bone.

The main analysis was the stress distribution and total deformation of bone graft and screws, as well as the pressure and sliding distances at three contact surfaces: (1) between the bone graft and the host bone; (2) between the bone graft and the metal cup; (3) between the metal cup and the acetabular host bone (Fig. 3).

RESULTS

Stress distribution and deformation of the bone graft

Fig. 4 shows the von Mises stress distribution and total deformation of the grafts from the front and back view. The stress of the RSC models is significantly lower than the Harris model's. The maximum values of the Harris0, Harris45, RSC0, and RSC45 models are 97.13 MPa, 112.72 MPa, 16.56 MPa, and 25.50 MPa, respectively. The same trend can also be seen in the total deformation. The maximum values are 0.022 mm, 0.018 mm, 0.0096 mm, and 0.0089 mm, respectively. The same graft shows higher stress and smaller deformation with 45° inserted screws.

When the screws were inserted at 45°, the maximum stress and deformation was mainly located on the outside of the bone graft, above the entrance of the screws. For the models with 0° inserted screws, the maximum

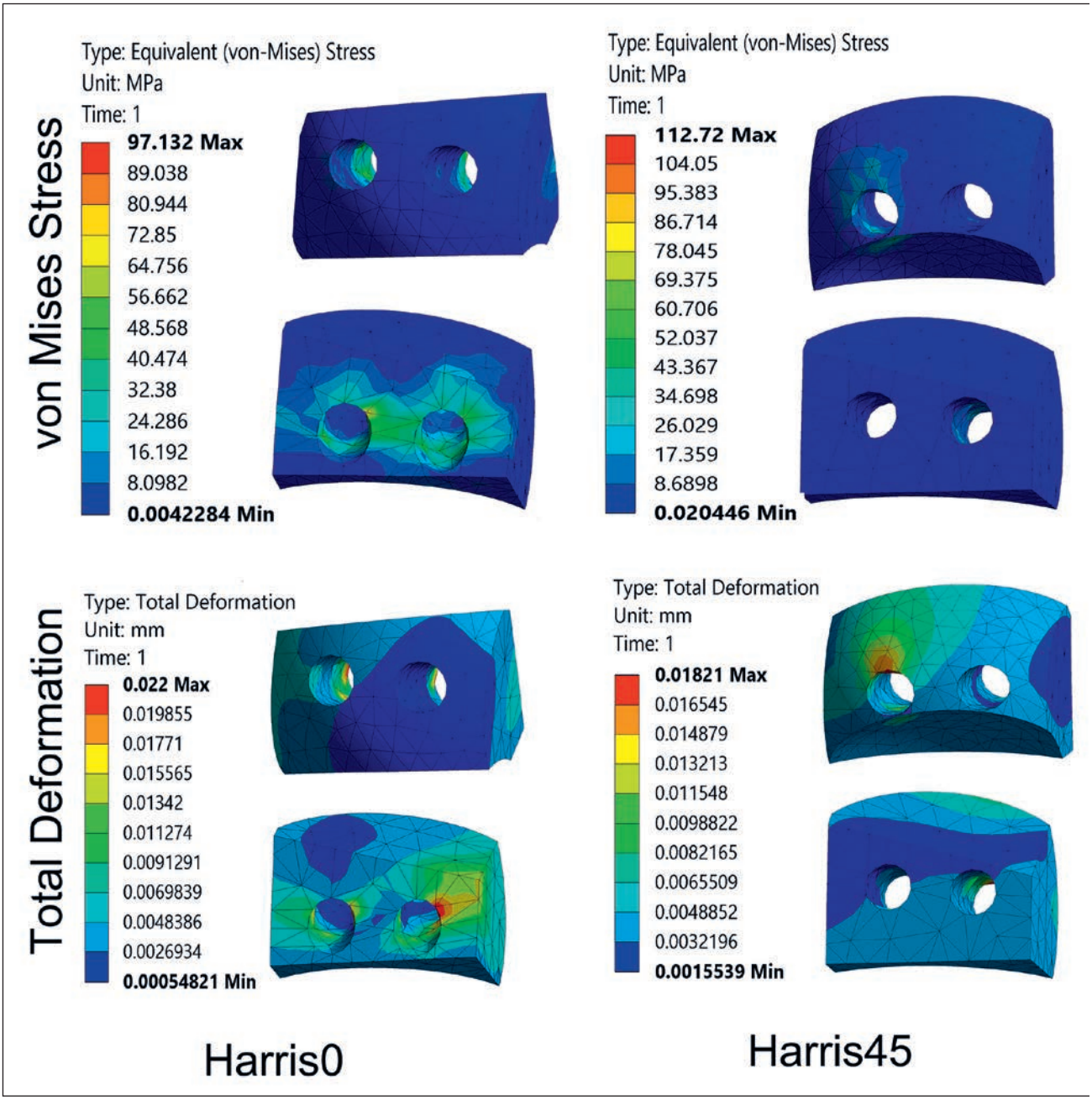


Fig. 4. von Mises stress distribution and total deformation of the grafts from the front (1st and 3rd row) and back (2nd and 4th row) view. Each column from left to right represents the model of Harris0 (BBG with 0° screws), Harris45 (BBG with 45° screws), RSC0 (step-shaped bone graft with 0° screws), RSC45 (step-shaped bone graft with 45° screws).

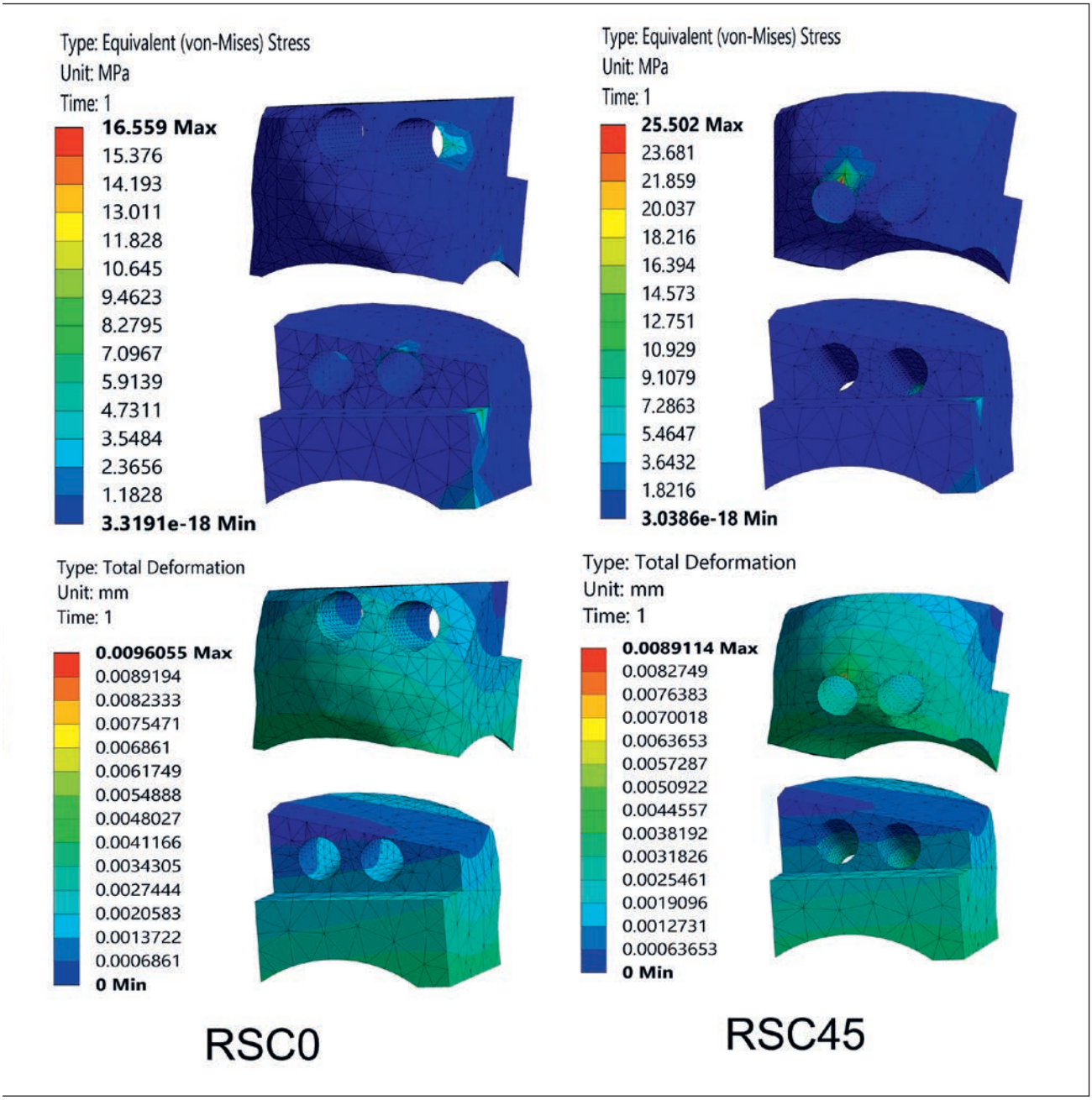
value is mainly located inside the screw channel as well as at the contact area with the host bone. However, the value of the RSC0 model is significantly lower than the Harris0 model.

Stress distribution and deformation of the screws

According to the result of FEA analysis, the maximum von Mises stress distribution of the screws in RSC models is significantly lower than the Harris models (16.56, 25.50 MPa vs 97.13, 112.72 MPa), and the maximum total deformation shows the same change as the bone graft. Harris0 model has the highest stress value and deformation. For bone grafts of the same shape, 45° inserted screws generated higher stress at the outer 1/3 area. For the horizontally inserted screws, the maximum stress value mainly locates at the middle of the screw (Fig. 5).

The pressure and sliding distance at different contact surfaces

The pressure and sliding distance were analyzed at three contacts: between the graft and the host bone, the graft and the metal cup, and the metal cup and the acetabular host bone. Fig. 6 and Fig. 7 show the differences between both indicators in the four models.



Generally, from Harris0 to RSC45, the pressure and sliding distance are decreasing. However, the Harris45 model shows a significant sliding effect between the metal cup and the acetabular host bone and the pressure at the contact between the graft bone and the metal cup is also the highest (Fig. 8). For the pressure and the sliding distance, the maximum value of the BBG is mainly located in the center of the contact area. In contrast, for the RSC model, it is primarily close to the edge.

DISCUSSION

This study aims to investigate for DDH cases during THA when an autologous bone graft is used to reconstruct the acetabulum whether the shape of the graft and the screws inserted direction could cause different biomechanical effects. Four models were established based on two techniques: the step-shaped bone graft and the BBG with 0° or 45° inserted compression screws. Using FEA analysis, the results showed that the step-shaped graft in the RSC technique could significantly reduce the stress and deformation of the graft and the screws. Also, it could significantly decrease the pressure and sliding distance on relevant contact surfaces.

The reason why THA surgery for DDH cases is more challenging is because of the specific anatomical and pathological characteristics of the acetabulum. Augmentation materials are usually needed to achieve better acetabular cup coverage, which is vital for the stability of the cup. Among all clinically available

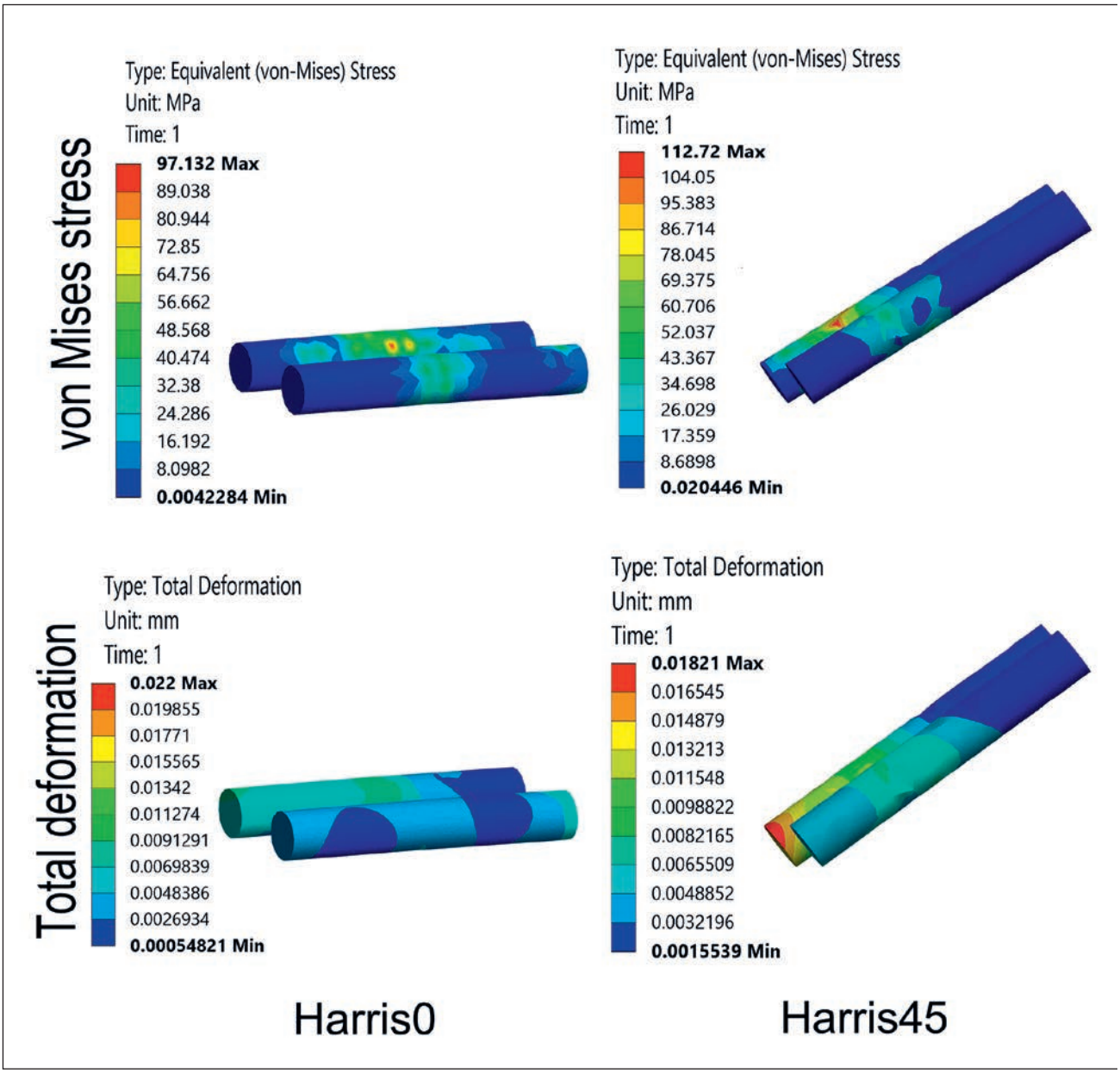
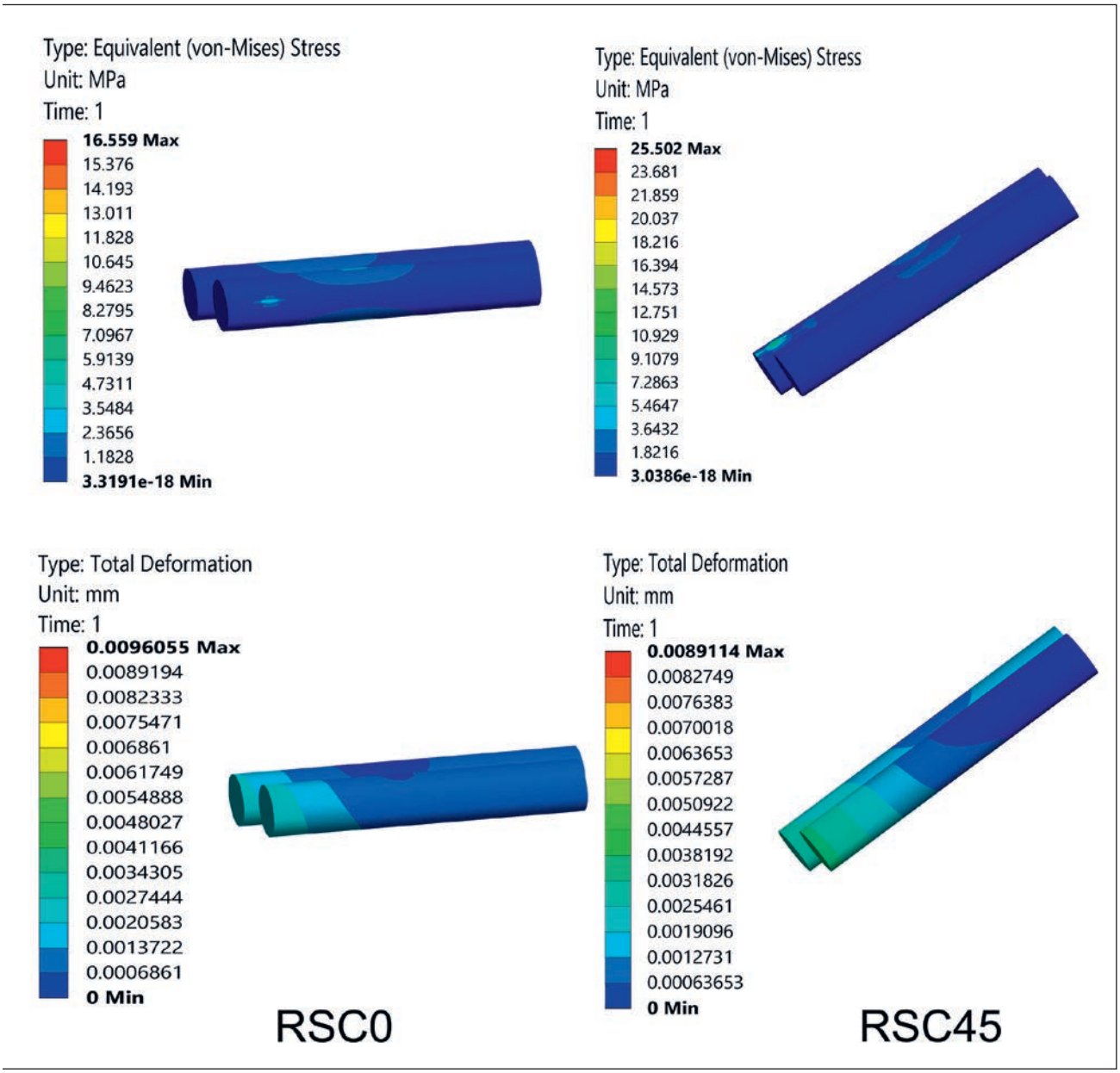


Fig. 5. von Mises stress distribution and total deformation of the screws. Each column from left to right represents the model of Harris0 (BBG with 0° screws), Harris45 (BBG with 45° screws), RSC0 (step-shaped bone graft with 0° screws), RSC45 (step-shaped bone graft with 45° screws).

grafts, autologous bone is still considered as the golden standard because from the perspective of bone regeneration, it has all the necessary properties in osteoconduction, osteoinduction and osteogenesis (14). As more and more DDH patients choose surgery at a relatively young age, taking into account future revision, proper bone stock restoration is obligatory. There are three main aspects to keep in mind. Firstly, the primary rotational center is superior to other cup positions. Secondly, cementless implant theoretically has better survivorship than cemented ones because it is very difficult to avoid cement being squeezed into the gap between the graft bone and the host bone, which will hamper bony ingrowth. Furthermore, cemented implant will increase the difficulty of future surgery. Thirdly, the consolidation of the bone graft should be achieved by new bone formation after partial resorption (5).

Bulk bone autografts have been used in DDH for a long time. Because of differences in patients' selection, the severity of dysplasia, bone quality and technique of application, the published results are quite varied. Cup loosening associated with failed bone incorporation is one of the leading causes of revision surgery (11). Young et al. reported that the key to success in acetabular bone graft is to establish a good fit of the graft into the host bone and good fixation. Clinical prognosis is irrespective of the size of the graft (22). Other studies also declared that graft stability and bone-graft contact are the main factors affecting graft incorporation (5). Therefore, the graft volume should be kept



at a sufficient level, and primary stability and direct cancellous-cancellous bone contact should be achieved. With similar width and height, compared to the bulk bone, the step-shaped graft in the RSC technique has a much larger cancellous bone contact area (937.2 mm^2 vs 674.1 mm^2).

Stress and micromotion could significantly affect the bone regeneration process. By animal model, Kim et al. found that the application of proper compression at an early consolidation stage induced faster and denser bone regeneration (10). In an analysis of fracture healing, it was reported that under high octahedral shear

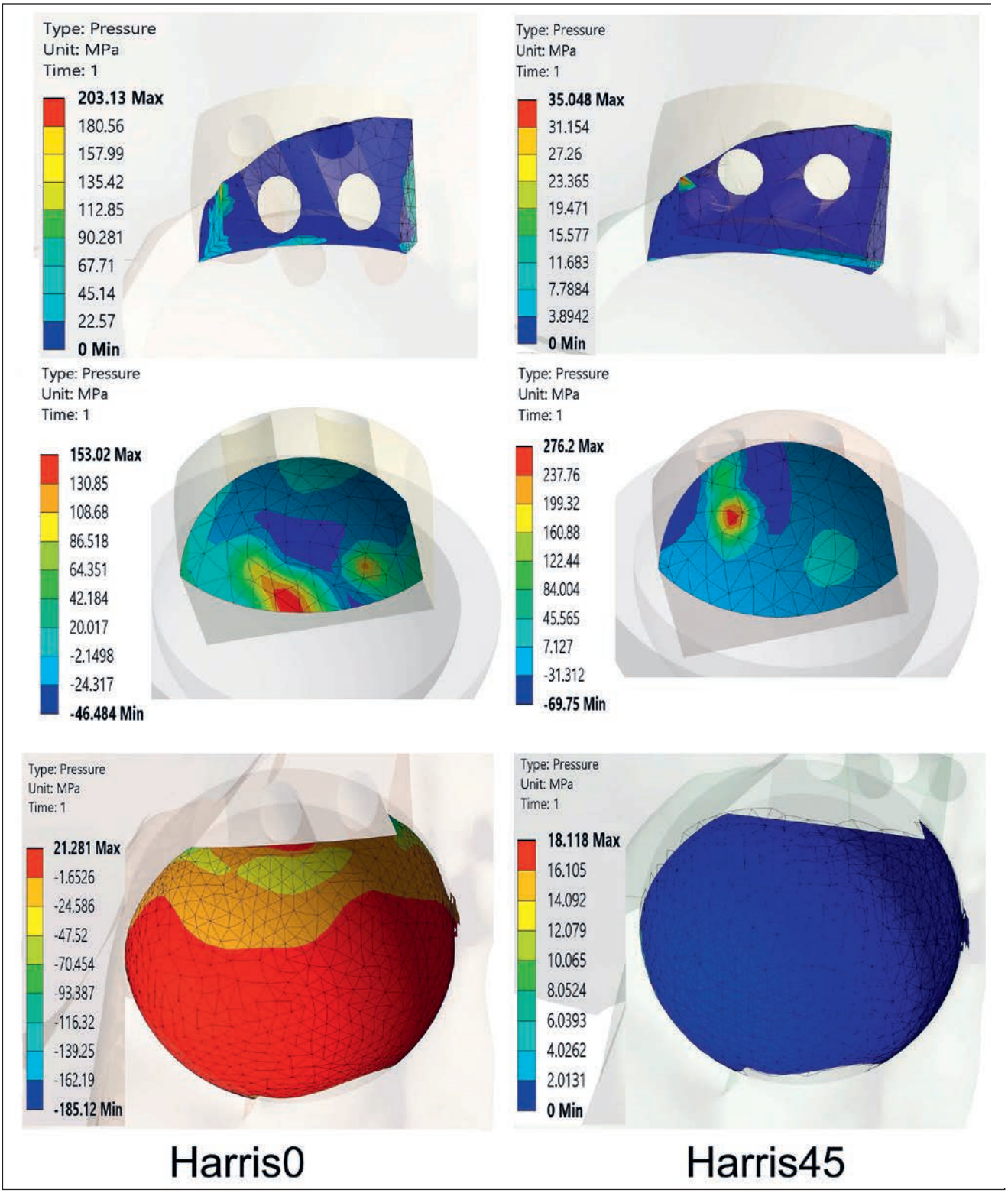
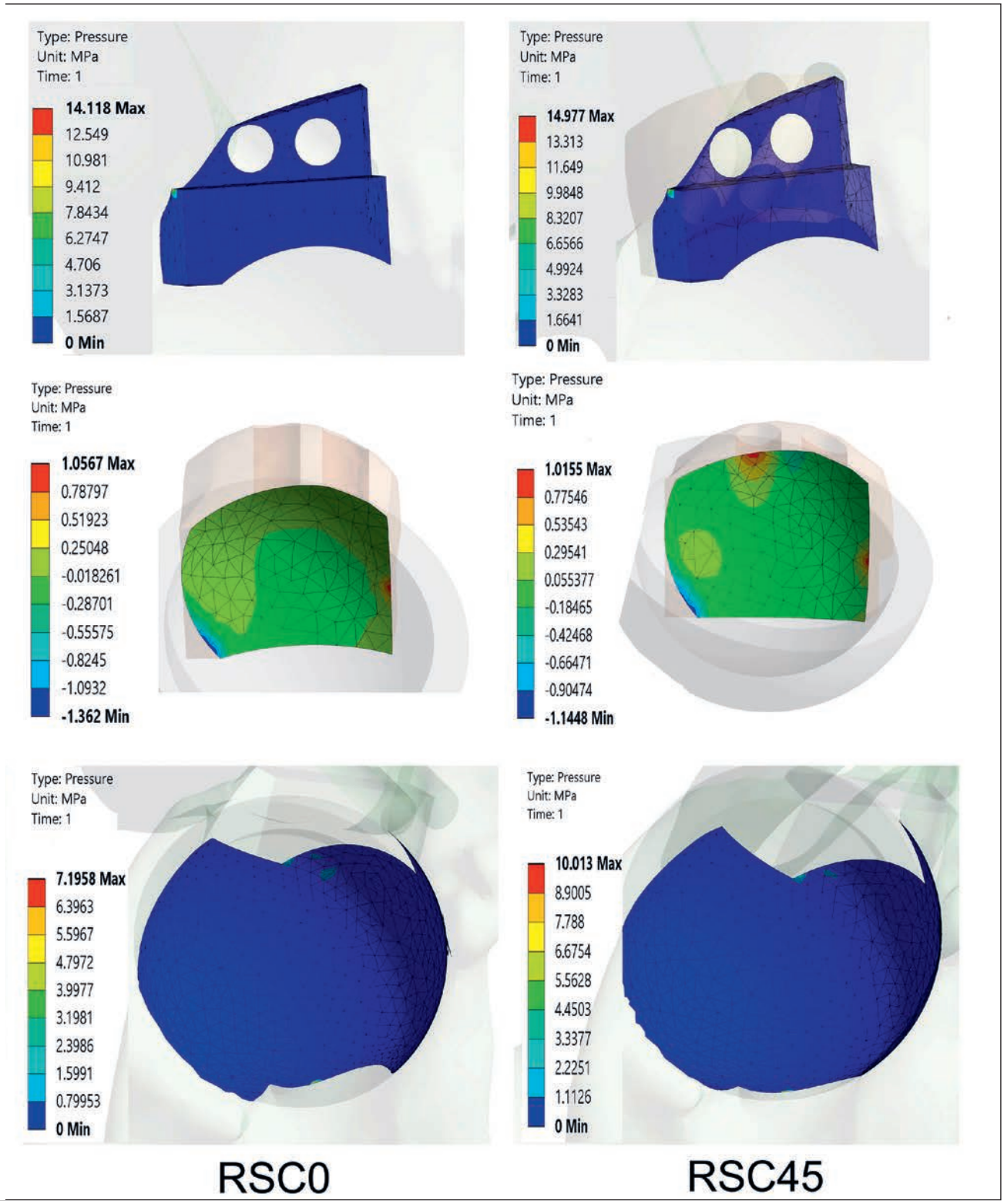


Fig. 6. Pressure distribution of all the models at three contacts: contact between the graft and the host bone (1st row), contact between the graft and the metal cup (2nd row), contact between the metal cup and the acetabular host bone (3rd row).

stress or maximum principal strain, both chondrogenesis and osteogenesis were inhibited, instead, the formation of fibrous connective tissue or fibrocartilage occurred (16). As for the micromotion, previous studies showed that a micromotion of > 150 μm leads to fibrous tissue formation, while adequate osseous contact and fixation minimizes micromotion and prevents fibrous ingrowth; micromotion between 30 and 150 μm leads to bone and fibrous tissue formation; and micromotion < 28 μm results in predominant bone formation (8, 18). In this study, compared to BBG model, the RSC technique could significantly reduce the maximum stress and



maximum total deformation of the graft and screws. The sliding distances at the contacts between the graft, the metal cup and the acetabular host bone are all less than 28 μm. For these reasons, the RSC technique is more beneficial for the incorporation of bone graft and host bone.

We hypothesized that the screw direction could affect the biological healing process of the graft. The results showed that in the BBG models, both 0° and 45° inserted screws presented with higher stress and larger deformation, especially the 0° inserted ones showed the highest values in the middle of the screws and also at the graft-host bone contact surface, both are critical areas for osseointegration and stability. Interestingly, with BBG and 45° screws, there was a significant sliding effect between the metal cup and the acetabular host bone, causing significantly higher pressure between the bone graft and the metal cup. The reason could be that the graft slightly moved upward along the screws during loading. However, in the RSC technique, because of the step-cut surface, it can block such movements. In the RSC step-shaped graft models, 45° inserted screws

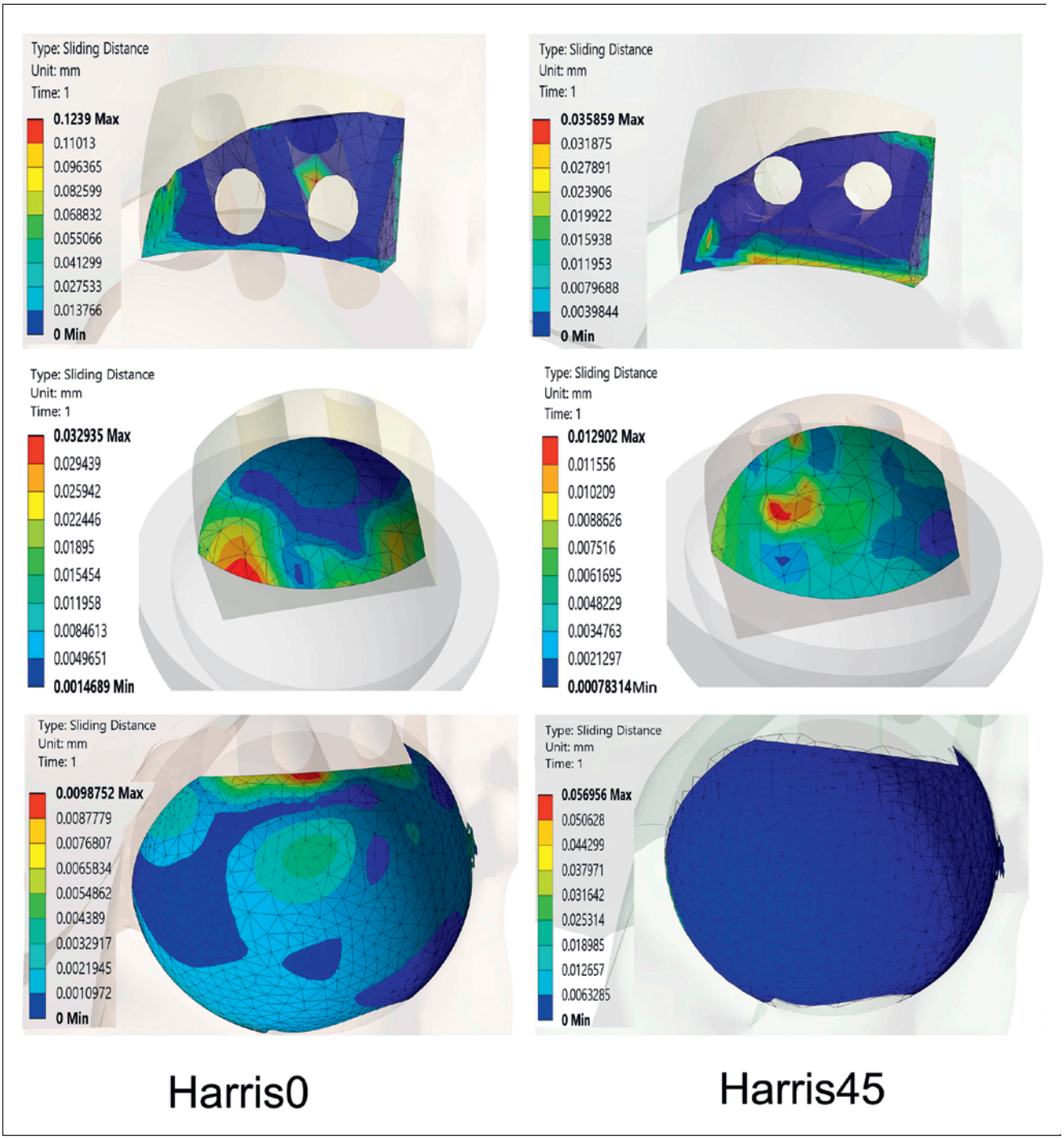
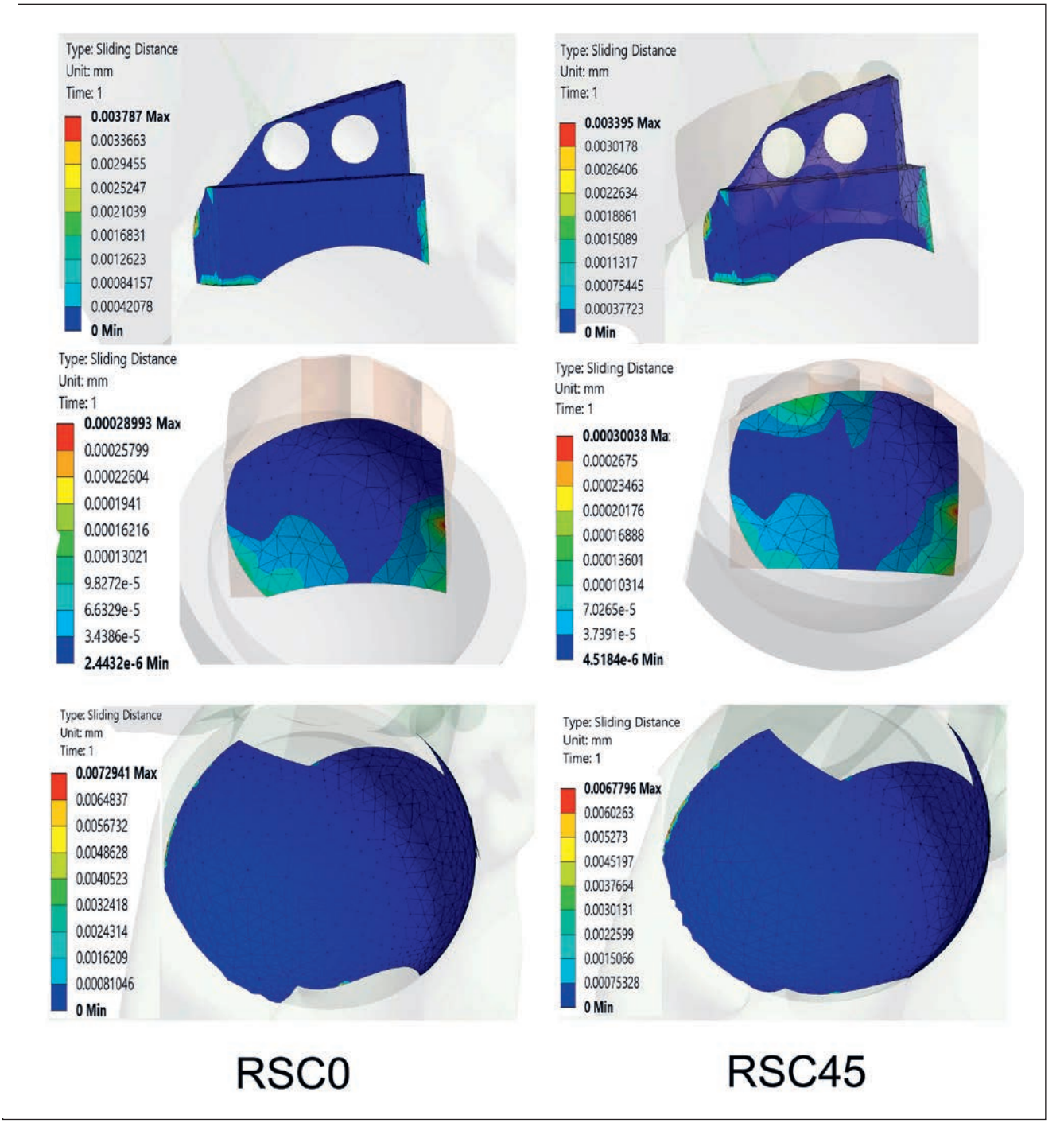


Fig. 7. Sliding distance analysis of all the models at three contacts contact between the graft and the host bone (1st row), contact between the graft and the metal cup (2nd row), contact between the metal cup and the acetabular host bone (3rd row).

showed higher stress and smaller deformation in comparison to the 0° inserted model, but the differences are not that significant. 45° inserted screws are still favored because for 0° inserted screws, the stress is mainly located in the middle region, which is the most fragile area and easy to break, while for 45° inserted screws, the stress is mainly located at the end of the screws, where in reality there is a pressing and locking effect between the screw head and the cortical bone (15), this way it can hold more strength and is better to maintain the stability. This is also the reason why it is recommended that when sculpting the graft from the femoral head, the outer cortical bone should be preserved.

The strength of this study is that the whole hip model is built, which the loading and constraint is as much as possible consistent with normal hip kinematics. Unlike other studies that designed and used regular-shaped bone grafts (9), the bone grafts in this study were sculpted from a solid sphere, which is closer to the actual surgical operation. The width and height of the two kinds of grafts were kept basically the same, to avoid the influence of graft bone size. Except for bone graft and screws, the



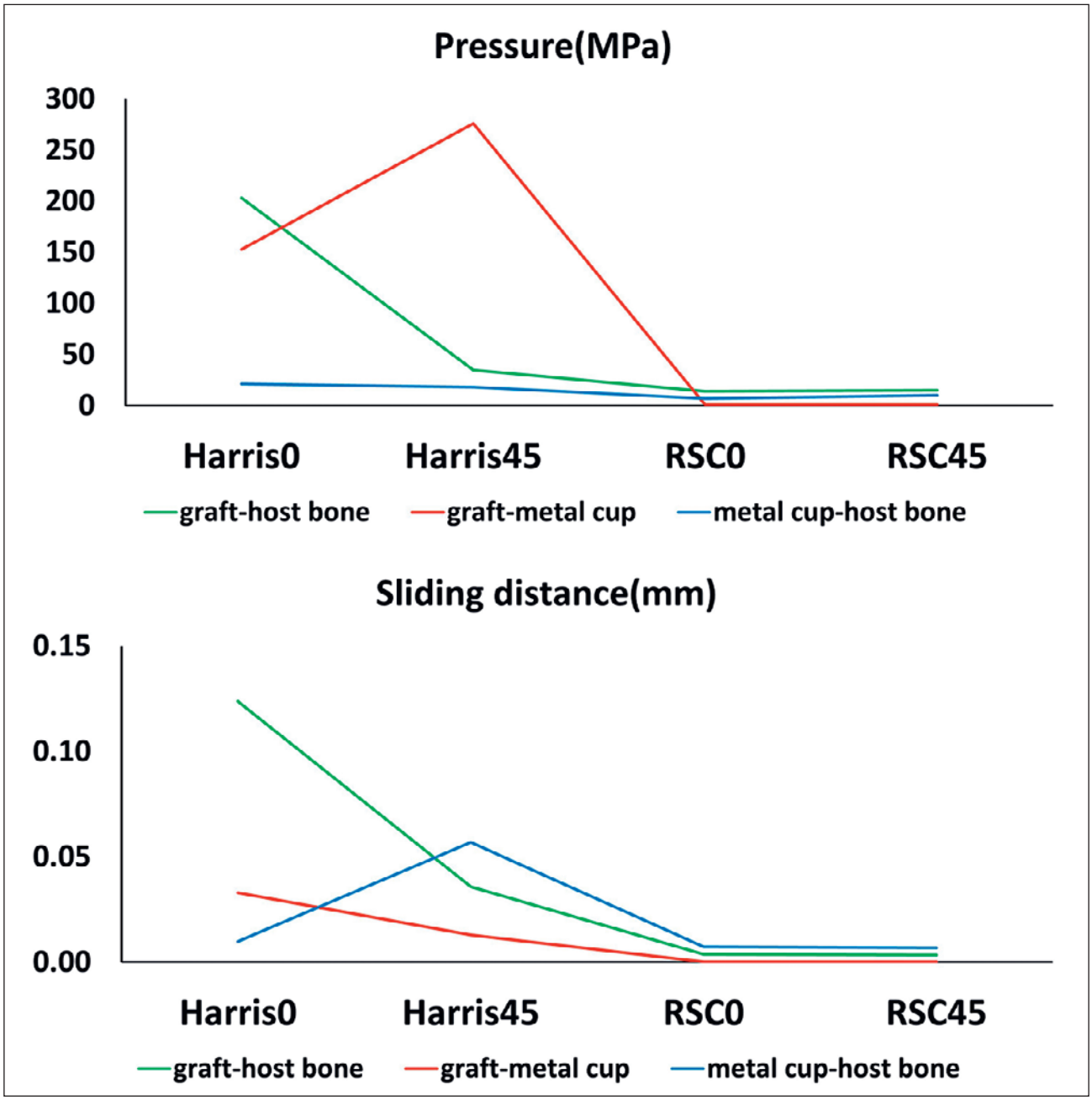


Fig. 8. Maximum pressure and sliding distance at the three contacts (between the graft and the host bone, the graft and the metal cup, and the metal cup and the acetabular host bone) in all models.

positions and parameter settings of other components are all the same, which also avoids the influence of interfering factors on the results. However, there are some limitations. This study established the ideal FEA models to analyze the biomechanical effect of the bone graft and screws, which can not completely mimic the actual surgical environment and real-life results. Stresses perpendicular to the contact surface are more favorable for graft integration than shear stresses, the differences in the effects of these stresses may require further study. In addition, due to the subchondral cyst in the femoral head or its serious deformation, the autogenous bone may be in limited supply and cannot be sculpted into the desired shape. Therefore, preoperative assessment is essential and our results proved that in the future, maybe it is necessary to have this „step-shaped" augment implant in the market to meet the surgical needs of patients who have too little or poor quality autologous bone.

CONCLUSIONS

Compared with the BBG technique, for the DDH cases during THA, the step-shaped graft of the RSC technique could significantly reduce the stress and de-

formation of the graft and the screws, decrease the pressure and sliding distance between the bone graft, metal cup and the acetabular host bone. The angle of screw placement affects the location of stress and deformation.

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