Clinical Case Report

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Three-dimensional reduction and finite element analysis improves the treatment of pelvic malunion reconstructive surgery

A case report

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Abstract

Rationale: Pelvic malunion is a rare complication and is technically challenging to correct owing to the complex three-dimensional (3D) geometry of the pelvic girdle. Hence, precise preoperative planning is required to ensure appropriate correction. Reconstructive surgery is generally a 2- or 3-stage procedure, with transiliac osteotomy serving as an alternative to address limb length discrepancy.

Patient concerns: A 38-year-old female patient with a Mears type IV pelvic malunion with previous failed reconstructive surgery was admitted to our department due to progressive immobilization, increasing pain especially at the posterior pelvic arch and a leg length discrepancy. The leg discrepancy was approximately 4 cm and rotation of the right hip joint was associated with pain.

Diagnosis: Radiography and computer tomography (CT) revealed a hypertrophic malunion at the site of the previous posterior osteotomy (Mears type IV) involving the anterior and middle column, according to the 3-column concept, as well as malunion of the left anterior arch (Mears type IV).

Interventions: The surgery was planned virtually via 3D reconstruction, using the patient's CT, and subsequently performed via transiliac osteotomy and symphysiotomy. Finite element method (FEM) was used to plan the osteotomy and osteosynthesis as to include an estimation of the risk of implant failure.

Outcomes: There was not incidence of neurological injury or infection, and the remaining leg length discrepancy was $\leq$2 cm. The patient recovered independent, pain free, mobility. Virtual 3D planning provided a more precise measurement of correction parameters than radiographic-based measurements. FEM analysis identified the highest risk for implant failure at the symphyseal plate osteosynthesis and the parasymphyseal screws. No implant failure was observed.

Lessons: Transiliac osteotomy, with additional osteotomy or symphysiotomy, was a suitable surgical procedure for the correction of pelvic malunion and provided adequate correction of leg length discrepancy. Virtual 3D planning enabled precise determination of correction parameters, with FEM analysis providing an appropriate method to predict areas of implant failure.

Abbreviations: 3D = three-dimensional, AP = anterior–posterior, CAD = computer-aided design, CT = computed tomography, FEA = finite element analysis, FEM = finite element method, NURBS = non-uniform rational basis splines, ROM = range of motion, STL = STereoLithography, Standard Tessellation Language.

Keywords: 3D virtual planning, finite element analysis, pelvic malunion, pelvic ring fracture, reconstructive surgery, surgical planning

1. Introduction

Pelvic malunion is a rare complication after pelvic ring fracture, with the incidence of malunion having decreased over the last few years owing to increasing use of early fracture reduction and internal fixation for unstable pelvic ring fractures, rather than conservative treatment and the use of external fixation.[1–4] Despite the effectiveness of early fracture reduction and internal fixation in reducing the rate of malunion, malunion does remain as a predominant complication of the treatment of type C pelvic ring fractures.[2,5–7]

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SK and PP have contributed equally to this work.

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The complex geometry of the pelvis, as well as the involvement of various reference landmarks, such as vertical displacement, rotational deformities, and acetabular configuration, makes it difficult to plan correction surgery.[1,8,9] The described correction procedures include 2 or 3 stages, and involve a change in the patient position (prone/supine) and reliance on the primary fracture as a reference for the following corrective surgery.[8–11] In addition, transiliac osteotomy—a well-known procedure for treating hip dysplasia—has been introduced as an alternative approach for pelvic malunion, particularly when limb lengthening is required.[6]

To ensure accurate planning, Henderson et al[1] and Mears and Velyvis[9] established x-ray-based measurements for reconstructive surgery. Nevertheless, the complex geometry of the pelvis is still not well represented with this method, and the need for three-dimensional (3D) planning tools or models has been previously presented.[2] Moreover, malunion correction requires a more rigid fixation, as compared with the initial fracture management, in order to prevent implant failure.[8,10] The finite element method (FEM) might be a suitable tool to assess the stability of the pelvis, as well as its fixation, in order to estimate the risk of implant failure.[12,13] In the present study, a modified transiliac osteotomy was performed, combined with a symphysiotomy, to treat a Mears IV malunion as a 2-stage procedure, without a need to change the patient's position. The surgical correction was virtually planned in advance, based on the 3D reconstruction of the patient's computed tomography (CT) images, and the risk of implant failure was ascertained by applying the FEM, which consequently affected the decision of postoperative weight bearing.[9]

2. Methods

2.1. Ethical statement

Written informed consent was obtained from the patient for the publication of this case report, including any accompanying images of the surgical planning and intraoperative. A copy of the written consent is available for review by the editor of this journal.

2.2. Case presentation

Four years prior to admission to our outpatient clinic, the patient had sustained multiple injuries from a suicide attempt, wherein she jumped through a window (height >10 m). The injury pattern included a severe head injury, including left frontal subarachnoid bleeding that overwhelmed the side ventricle, diffuse axonal injury, traumatic lesion of the brain stem leading to paresis of the oculomotor nerve, anisocoria, lesion of the infraclavicular part of the brachial plexus, a left pneumothorax, lung contusions with serial rib fractures (ribs 1–3) on the right side, a fractured right acromion, as well as an unstable fracture of the right pelvic ring (Young and Burgess type CM, OTA/AO 61 C1.2.1 modificator C2). After the implantation of an intracranial pressure probe, the pelvic ring fracture was stabilized via plate osteosynthesis at the iliac crest and at the anterior arch bridging the symphysis. Nevertheless, optimal fracture reduction was not achieved, probably due to head and lung injury. After surgery, the patient could walk and did not experience any pain. However, after 1 year, the patient was again admitted with a leg length discrepancy of 2.3 cm and pain during weight bearing. There were no signs of instability or a reduction in the range of motion (ROM) of the hip joints. Due to the presence of severe pain and progressive loss of mobility, material removal, correction osteotomy, and osteosynthesis were performed. An osteotomy was made through the old fracture, with a diastasis of 9 mm, and fixation via plate and screw osteosynthesis of the right ilium and plate osteosynthesis of the left anterior arch was performed. However, the leg length discrepancy could not be completely corrected during this procedure. After discharge, the patient did not complain of pain or mobility impairment. At 6 months after the surgery, radiography indicated material failure at the right pelvic ring due to reported pain at the osteotomy site and the right sacroiliac joint (Fig. 1). Nevertheless, the patient could walk without any orthopedic aids. Further correction surgery was planned, but the patient refused any additional surgeries. After 2 years, the patient (at 40 years of age) was admitted to our outpatient clinic. She had developed progressive loss of mobility and was only able to walk using forearm crutches. Painkillers and physiotherapy did not reduce the pain, and the pain at the sacroiliac joint had increased. Furthermore, the leg lenght discrepancy had increased to 4 cm, and rotation of the right hip joint was associated with pain. Dyspareunia, vaginal impingement, and sitting discomfort were not observed. The radiographic imaging revealed a hypertrophic malunion at the site of the posterior osteotomy (Mears IV) involving the anterior and middle column, according to the 3-column concept, as well as malunion of the left anterior arch (Mears IV).[9] The patient desired further correction surgery that was planned using 3D reduction and the FEM to improve her outcome.

2.3. Radiographic measurements

Vertical displacement, according to the methods of Henderson et al,[1] was measured using anterior–posterior (AP) radiographs by drawing a vertical line through the fourth lumbar vertebra and

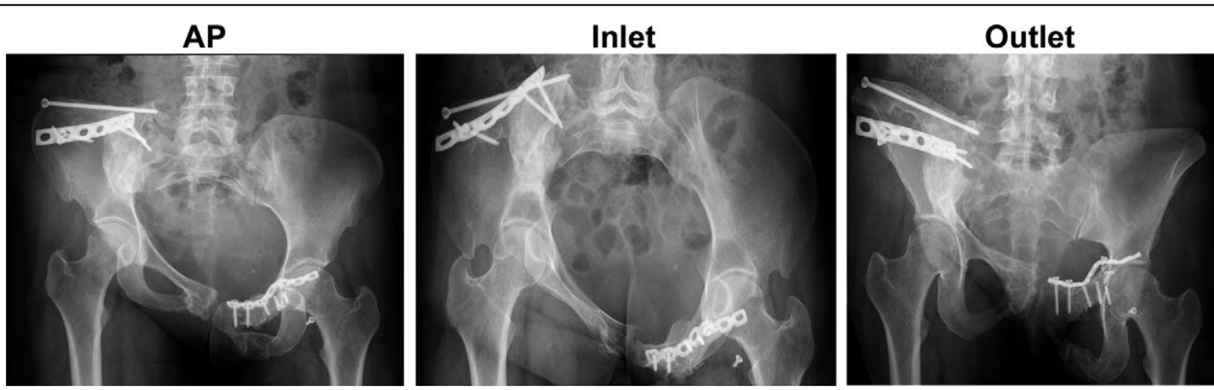

Figure 1. Preoperative radiographs indicating the vertical, anterior–posterior (AP), and rotational displacement.

2 perpendicular lines at the highest points of each iliac wing; the difference in these lines of the iliac wings represented the vertical displacement. The malalignment had to be modified for the measurement of AP displacement on the inlet radiographs. A line was drawn through the spinal processes of the lumbar spine and the sacrum, as a reference. Two lines were drawn perpendicular to this line and through each ischial spine. The difference between the ischial lines represents the AP displacement.

Mears and Velyvis[9] noted rotational or vertical displacements in 34% of patients with symptomatic limb length discrepancy. Hence, rotational instabilities were assessed on the inlet radiographs by drawing a line through the middle of the sacrum and measuring the angles from this line to the lines drawn along each iliac bone. A difference >15° was considered as a deformity, depending on their direction (internal or external rotation). AP instability was measured using inlet radiographs, wherein lines were drawn from the most posterior aspect of the iliac wing perpendicular to the sacrum; a difference ≥1 cm indicated AP instability. Vertical displacement was measured from outlet radiographs by drawing lines from the highest point of the ilium, perpendicular to the corresponding lumbar vertebra or sacrum; a difference >1 cm was defined as vertical displacement.[9] Leg length discrepancy was measured by drawing a line through the spinal processes of the lumbar spine and 2 lines drawn perpendicular to the acetabular roof; the resulting difference was calculated from the AP and outlet radiographs.[14]

2.4. Geometry creation

Virtual planning was initiated 6 weeks before surgery. The bony morphology was semiautomatically segmented in *Mimics 16* (Materialise NV, Leuven, Belgium) based on the pelvic CT scans, and was exported with stereolithography (STL, Standard Tessellation Language).

During the geometry pre-processing stage using *Geomagic Design X* (3D Systems, Rock Hill, SC), the tessellated surfaces were transformed in Non-uniform Rational Basis Splines (NURBS) via exact surface reconstruction. Following topological discrepancy verification between the imported DICOM data and the generated NURBS geometry, the data were transferred to *SolidWorks* (Dassault Systèmes SolidWorks Corporation, Vélizy-Villacoublay, France). The bones were combined to assemblies in relation to the coordinate system, given by the CT dataset; accordingly, the soft tissue (cartilage) was designed by using anatomical landmarks from the CT data.

2.5. Virtual resetting and implant planning

The osteotomy was planned based on the virtual pelvic model. Within the model, the following criteria were defined:

- the osteotomy should be made at the old fracture site, and the limb length discrepancy should be addressed[6];
- an additional osteotomy might be performed without inducing an instability;
- the acetabular rotation does not change;
- the leg lengthening does not exceed 3 cm, and is a minimum of 2 cm[15];
- rotational correction does not exceed 15° of the internal or external rotation[9];
- vertical displacement should be completely corrected.[9]

The resulting osteotomy is presented in Fig. 2A. Thereafter, implant localization of the geometrically simplified implants was performed, and the implants were virtually positioned. A 10-hole plate was set on the iliac crest, a 7-hole plate was set on the pelvic brim, and a 4-hole plate was set on the symphysis pubis (Fig. 2B). The screws were simplified by modeling them as cylinders with a consistent diameter.

2.6. Finite element modeling

Numerical simulation was performed according to preoperative virtual planning with ANSYS (version 16, ANSYS Inc., Canonsburgh, PA), after transferring the computer-aided design (CAD) model to ANSYS. Modeling parameters were set based on the study of Böhme et al,[13] and the discretization was performed using proximity- and curving-based sizing functions. Mesh optimization was achieved via a series of mesh analyses, until the peak stress difference between the current and the last iteration was <2%. The whole model, except for the screws, was meshed using higher order 3-D-10-node elements, and quadratic displacement behavior (SOLID187), and the cortical layer was modeled with a minimum of 4 layers of elements. Higher order 3-D and a 20-node solid element that exhibits quadratic displacement behavior (SOLID186) were used for the screws.

Cortical and cancellous bones were assigned differing linear-elastic and isotropic material properties based on the differing stiffness properties (Table 1).

The contact conditions between the fracture parts, and between the bone and screws were modeled as bonded to simulate a partial consolidated fracture after 6 weeks. Between

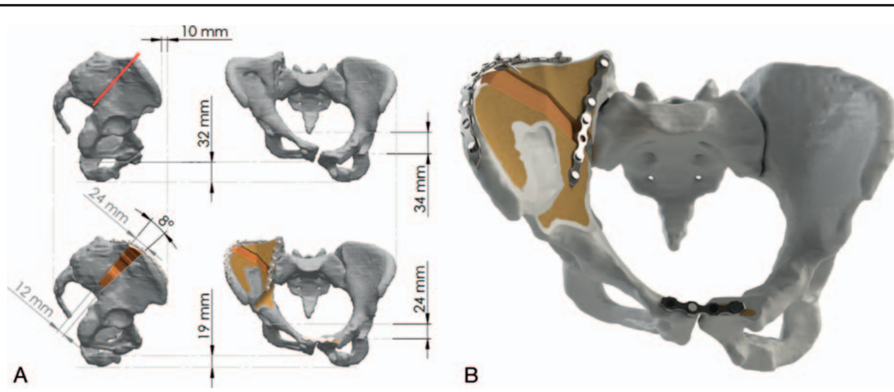

Figure 2. Virtual 3D planning for osteotomy and fixation, and the determined parameters of correction. A, Planned osteotomy in all planes, with the indicated parameters to correct. B, Planned reduction and implant positioning.

Table 1

Material properties used in the patient-specific finite element model[13].

Material	Young modulus (MPa)	Poisson's ratio
Cortical bone	8000	0.3
Trabecular bone	800	0.3
Cartilage	150	0.02
Titanium	110,000	0.3

the plates and the screws, a bonded contact definition was applied. The screws were modeled as fully threaded.

The main support was set at the promontory of the sacrum as an external displacement, with disabled translational and rotatory degrees of freedom. The load conditions were calculated in reference to the load case level walking as reported by Bergmann et al,[16–18] as shown in Table 2. The load caused by the supporting leg was assumed to be the patient's body mass, whereas the load on the free leg was calculated using the following equation:

$$F_{G_{fl}} = m_p(0.1289 + 0.0434 + 0.0129)g \quad (1)$$

where $F_{G_{fl}}$ is the effective force of the free leg, m_p is the patient's body mass, and g is the gravitational acceleration. The bracketed content reflects the relation between the mass of the respective part of the patient's leg and the patient's body mass:

$$m_{\text{thigh}} = 0.1289m_p, \quad (2)$$

$$m_{\text{shank}} = 0.0434m_p, \quad (3)$$

$$m_{\text{foot}} = 0.0129m_p. \quad (4)$$

Based on the formulation of Frost,[19] strain in the range of 0.2% to 0.4% can lead to loosening of dental and orthopedic bone implants, and was used in the present study to assess the risk of implant failure.

2.7. Surgical procedure

The patient was positioned in the supine position, and the first window of the ilioinguinal approach was selected for transiliac osteotomy.[6,15] The material was removed, iliac bone was prepared dorsally and ventrally prior to osteotomy, and the malunion-related callus was subsequently used as bone graft. In contrast to previous procedures, the old fracture represented the insertion point in our protocol, but was not completely used for osteotomy in order to ensure appropriate limb lengthening. After debridement, callus resection and osteotomy, the Stoppa approach was adopted to remove the remaining material at the anterior arch, and a symphysiotomy was performed in order to increase the potential for 3D correction. At the iliac wing osteotomy site, a laminar spreader was inserted under fluoroscopic control, and correction was performed. Additional correction was also performed using another laminar spreader at the symphysiotomy site. Once appropriate correction was achieved and the limb length discrepancy was resolved, the anterior arch was fixed via a 4-hole plate osteosynthesis without bone grafting. Thereafter, the dorsal osteotomy was augmented with the callus of the malunion and artificial cancellous bone. For fixation, plate osteosynthesis was performed at the iliac crest and the pelvic brim.

Table 2

Calculated load conditions on the supporting leg.

	Forces (N)
$F_{x_{sl}}$	892.710
$F_{y_{sl}}$	2643.795
$F_{z_{sl}}$	240.345

3. Results

3.1. Radiographic measurements

The AP displacement on the inlet view was 4.048 cm, and no vertical displacement on AP radiographs was observed, using Henderson's method.[1] Based on the measurements of Mears and Velyvis,[9] an internal rotation of 7°, symphyseal diastasis of 0.513 cm, AP displacement of 0.536 cm, and vertical displacement of 4.739 cm were observed. The leg length discrepancy was found to be 2.578 cm on AP radiographs and 4.059 cm on the outlet view.[14] 3D-measured displacement indicated an AP displacement of 0.63 cm, vertical displacement of 2.08 cm, and a sagittal malrotation of 6.8°.

For postoperative analysis, radiographs, obtained 3 months after the procedure, were examined (Fig. 3). A remaining posterior displacement of 2.403 cm, without any vertical displacement, indicating an AP displacement correction of 1.681 cm, was identified, using Henderson's method.[1] Based on the method of Mears and Velyvis,[9] postoperative radiographs revealed an external rotation of 8°, with a symphyseal diastasis of 1.328 cm, a remaining vertical displacement of 0.552 cm, and an AP displacement of 0.477 cm. The rotational difference was 15°, and the internal rotation error was corrected, as reflected by an increase in the symphyseal diastasis of 0.815 cm. The vertical displacement correction was 4.178 cm, with an AP correction was 0.059 cm. The remaining leg length discrepancy was found to be 1.588 cm on AP radiographs and 2.008 cm on the outlet view, thus indicating an elongation of 0.99 cm on AP radiographs and 2.051 cm in the outlet view. The planed correction involved a reduction of the AP displacement by 0.1 cm, vertical displacement by 2.66 cm, and rotational malrotation by 13.8°. Based on the classification of Mears and Velyvis,[9] a satisfactory outcome was achieved, as reflected by a displacement (vertical and/or posterior) of $\leq$1 cm and/or a rotational deformity $<$15°.

3.2. Postoperative course and the influence of FEM-based implant stability estimation

Postoperatively, the patient did not show any signs of wound infection or neurological deficits, and was discharged without complications after 7 days. As expected, finite element analysis (FEA) indicated a high strain in the area of the screws directly below the pubic symphysis (Fig. 4A). The area of highest pubic strain (0.5%; 0.005 mm/mm) was located at the contact area of the screw heads, plate, and cortical layer, at which point the plate showed the highest strain as well (Fig. 4B). At the pelvic brim, the screws caused higher strain at the cortical inlet area (Fig. 4C).

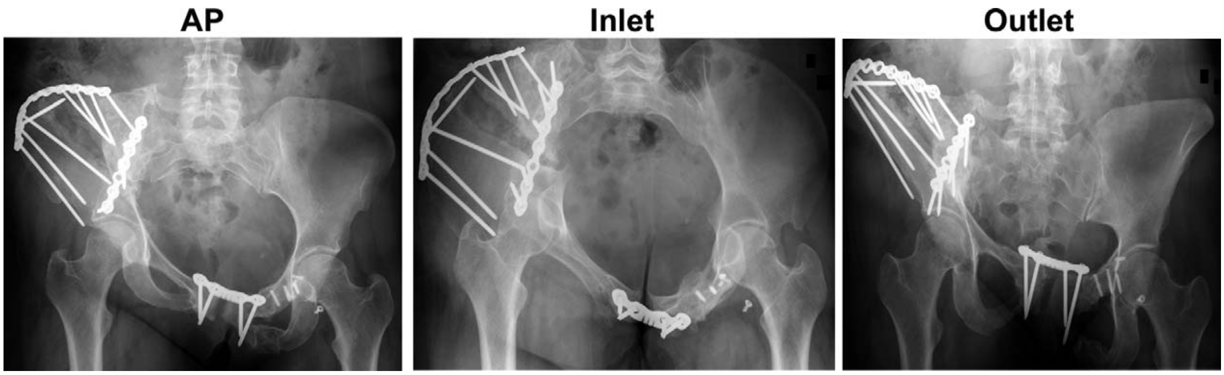

Figure 3. Postoperative radiographs indicating a reduction in limb leg discrepancy, as well as in the vertical, anterior–posterior (AP), and rotational displacement, as compared with the preoperative radiographs.

Implants located in the iliac crest caused the highest strain adjacent to the inner border of the cortical layer (Fig. 4D). All the simulated cortical strain values were significantly below the loosening strain range of 0.2% to 0.4%; no screw loosening was expected with the planned osteotomy.

Based on FEA and literature reports, weight bearing was restricted for 6 weeks, and the patient was transported via a wheel chair.[6,7,10,11] After 6 weeks, weight bearing was initiated during physical therapy with an antigravity treadmill, and was increased by 10% of the patient's body weight on a weekly basis. Full weight bearing was achieved 2 months after the beginning of physical therapy, with a single forearm crutch required for walking. On clinical examination, the patient did not report any pain on palpation or walking, and presented with reduced hip flexion (10°) and external hip rotation (10°). The patient exhibited an affected gait, which was probably related to the

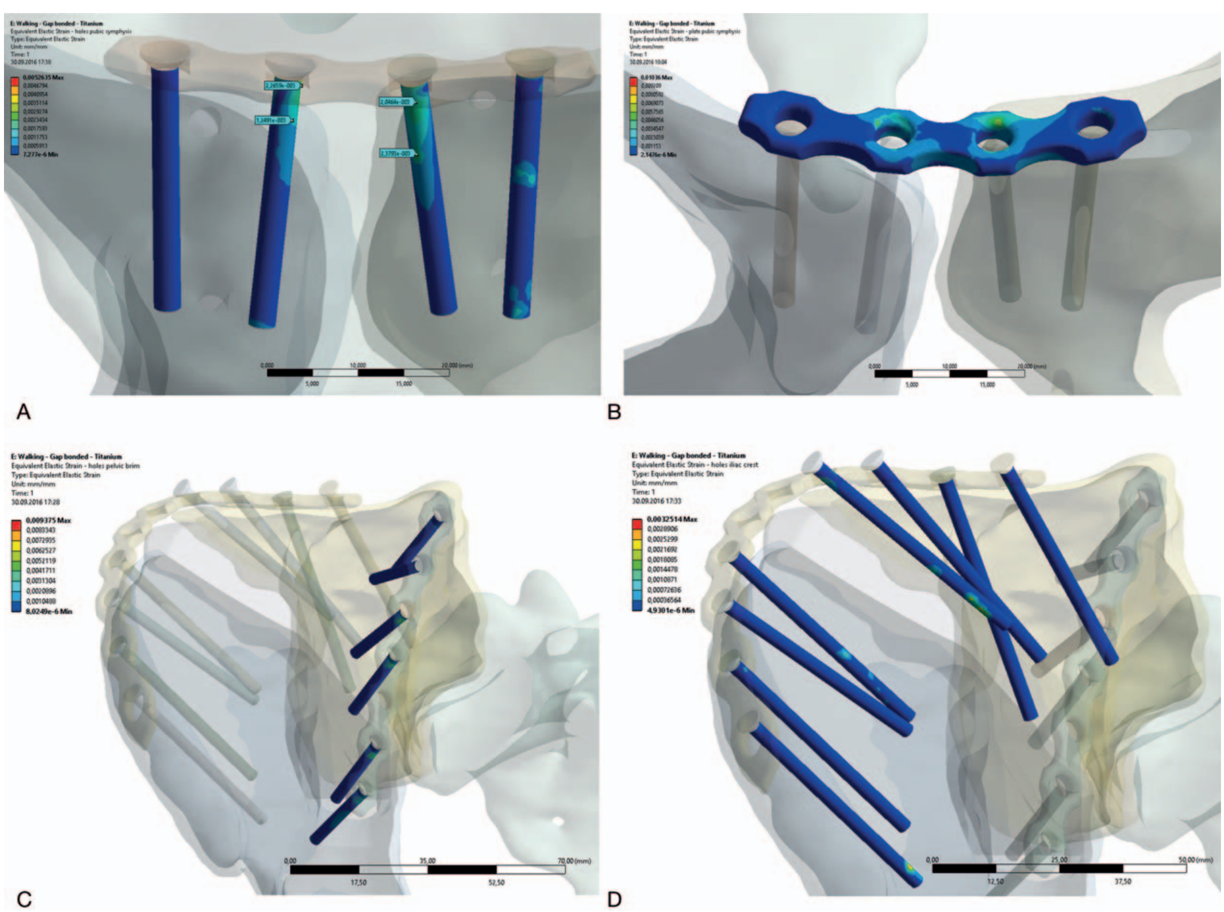

Figure 4. Resulting strain values on screw holes and symphyseal plate osteosynthesis; all the sustaining areas are under 0.3% strain. A, Strain on the symphyseal screw holes; the highest strain was noted at the parasymphyseal screws. B, Strain on symphyseal plating; the highest strain was noted at the parasymphyseal holes. C, Strain on the holes in the pelvic brim; the highest strain was noted at the upper screw shanks. D, Strain on the holes in the iliac crest; the highest strain was noted at the lower screw shanks.

long duration of incorrect loading. Additional physiotherapy corrected this gait impairment after 8 weeks, and the patient was pain free and could walk without forearm crutches. Radiological examination did not show implant loosening or indications of non-union or malunion.

4. Discussion

Although pelvic type C fractures have an increased risk for pelvic malunion, the overall pelvic malunion incidence has decreased due to a reduction in the use of conservative treatment and the sole application of external fixation over the last few years.[2,5–7] Nevertheless, precise data on the incidence of pelvic malunions after internal fixation remain scarce.[7]

The main causes of pelvic malunion include inappropriate reduction, ligamentous instability, and muscle pull that increases the displacement or are located between the fracture fragments.[2,7] Pain at the site of pelvic malunion (anterior or posterior) or at the low back, due to compensatory spine deformities, is the dominant symptom in patients with pelvic malunion.[2,6,8] Patients might also complain about gait disturbance, dyspareunia, vaginal impingement, sitting discomfort, and limited hip range of motion.[2,8] Leg length differences of clinical relevance were only observed in approximately 25% to 34% of patients.[2,9] In contrast, sitting discomfort related to ischial tuberosity deformity was reported in 50% of patients.[9] Nevertheless, due to the lack of specificity of clinical tests, pain due to malunion or the subsequent deformities represents a major indication for surgical correction.[9,20,21]

The most common approach to corrective surgery involves a 2 to 3 stage procedure, which requires a change in the position of the patient from prone to supine, and uses the old fracture for establishing the correction.[8–11] Postoperatively, most patients reported intermittent pain, and only 7.3% were not satisfied with the procedure.[9] In addition, approximately 50% of patients had a normal gait, and the same number of patients achieved anatomic correction.[9] However, achieving adequate correction in all 3 planes—axial, sagittal, and coronal—as well as vertical displacement has been reported to be the most technically challenging component of this reconstructive surgery.[9,22] Moreover, correction of the limb length discrepancy increases the complexity of the procedure and cannot be realized through pelvic correction alone.[20] In contrast, transiliac osteotomy, as an alternative approach for treating pelvic malunions and their related deformities, can enable limb shortening by approximately 3 cm.[6,15,23] However, this type of osteotomy cannot correct rotational deformities, an additional osteotomy is required.[6] In the present study, corrective surgery comprising transiliac osteotomy, to correct the limb leg discrepancy, and symphysiotomy to address the rotational deformity, were performed, enabling the patient to walk without any orthopedic devices and pain. In addition to correcting leg length discrepancy, this procedure does not require a change in the position of the patient during surgery and, hence, reduces the overall time for the surgical procedure.[6] Moreover, with this approach, the dissection of the sacrotuberal and sacrospinal ligaments is not required, thus decreasing the risk of ligamentous instability.[6,8,10–12,22] Postoperatively, no neurological deficits or other complications were observed in our case. Nevertheless, a complication rate of 19% to 24% following pelvic malunion correction has previously been reported.[2,10,21]

As the correction of pelvic malunions is technically challenging, appropriate preoperative planning is essential, including radiographic (AP, inlet, outlet) and CT imaging.[2,9,10,21] Although several authors have indicated the need for 3D-reconstructed CT images for planning, the measurements and related corrective procedures were planned using radiography or 3D prints of the deformity.[1,2,9] In the present study, 3D reconstruction of the pelvic malunion was used and the corrective surgery was planned virtually, allowing us to evaluate the potential effectiveness of several types of osteotomies and, thereby, optimize the surgical outcomes. In fact, different angles of lateral osteotomy and a ventral osteotomy lateral to the left of the pubic symphysis were evaluated, and the most promising approach was selected. By using this method, the rotational deformity and limb length discrepancy was corrected in a satisfactory manner, as per the classification of Mears and Velyvis.[9] Moreover, radiological evaluation indicated satisfactory results, and hence, a non-anatomical reduction may yield excellent outcomes,[3] as noted for our patient.

Compared with the fixation of acute injuries, a more rigid fixation of pelvic malunion correction is recommended to prevent implant failure.[8,10] However, no biomechanical or clinical studies have described data on the stability of fixation for treating pelvic malunions thus far, probably due to the decreasing incidence of the condition. FEM may be used to test the stability of implants in individual cases, and can accordingly indicate implant failure and pelvic stability.[12,13,24,25] The lack of any biomechanical and clinical studies may also be a reason for the various postoperative weight bearing protocols used, ranging from limited weight bearing, bed to chair mobilization, and partial weight bearing for 6 weeks to 3 months.[2,6,9,10,21] Based on these reports, it is recommended that weight bearing should be limited for 3 months, and at least for 6 weeks, followed by a progressive increase in weight bearing.[6,7,10,11]

It is known that the bonded contact formulation between screws and bone approximates ingrown threads, which requires low strain values which can only be achieved when the implants are well integrated. Based on these recommendations and the missing convergence on the initial FEA without bonded contacts between screws and bone, the patient was not permitted any weight bearing for at least 6 weeks. By using FEM, only 2 screws were found to be at risk of loosening; however, the patient did not complain of any pain, and no implant failure was observed in accordance with the results of the FEA.

Based on clinical outcomes and the patient's self-report of absence of pain, and considering the fact that the stability of the remaining components of the osteosynthesis (as observed on FEA), a progressive weight bearing protocol was initiated in our patient using an anti-gravity treadmill. Fourteen weeks after surgery, or 8 weeks after the start of weight bearing, the patient was able to walk using only one forearm crutch. Following additional physiotherapy, the patient recovered full independent walking capacity, without any orthopedic aids, with no complaints of pain 6 months after surgery.

In conclusion, pelvic malunions are challenging to correct and generally require a 2/3-stage procedure. The use of a transiliac osteotomy enabled limb lengthening along with correction of the vertical displacement. Through an additional osteotomy or symphysiotomy, the correction of rotational deformities of the pelvic girdle can also be performed in all 3 planes. Due to the technically challenging nature of the procedure, precise preoperative planning is required. In contrast to previous studies, we used 3D-reconstructed CT images to establish a virtual osteotomy plan, which yielded good results, as noted via conventional radiography. Furthermore, FEM not only helped estimate the risk of implant failure, but also aided in determining postoperative weight bearing. However, the limitations of applying FEM in the surgical planning need to be noted. Foremost, the clinical presentation of the patient always needs to be taken into consideration. Furthermore, non-consolidated fractures or fractures during healing are difficult to simulate owing to patient-specific characteristics, such as the magnitude of external loads and the conditions of loading, material properties, and fracture healing time. Moreover, the FEM requires significant computational costs. Approaches such as the element-free Galerkin method and biomechanically constrained filtering frameworks may improve these issues.[26,27]

Nonetheless, the patient's clinical outcome was excellent, in terms of both function and pain, consistent with the satisfying radiological results.

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