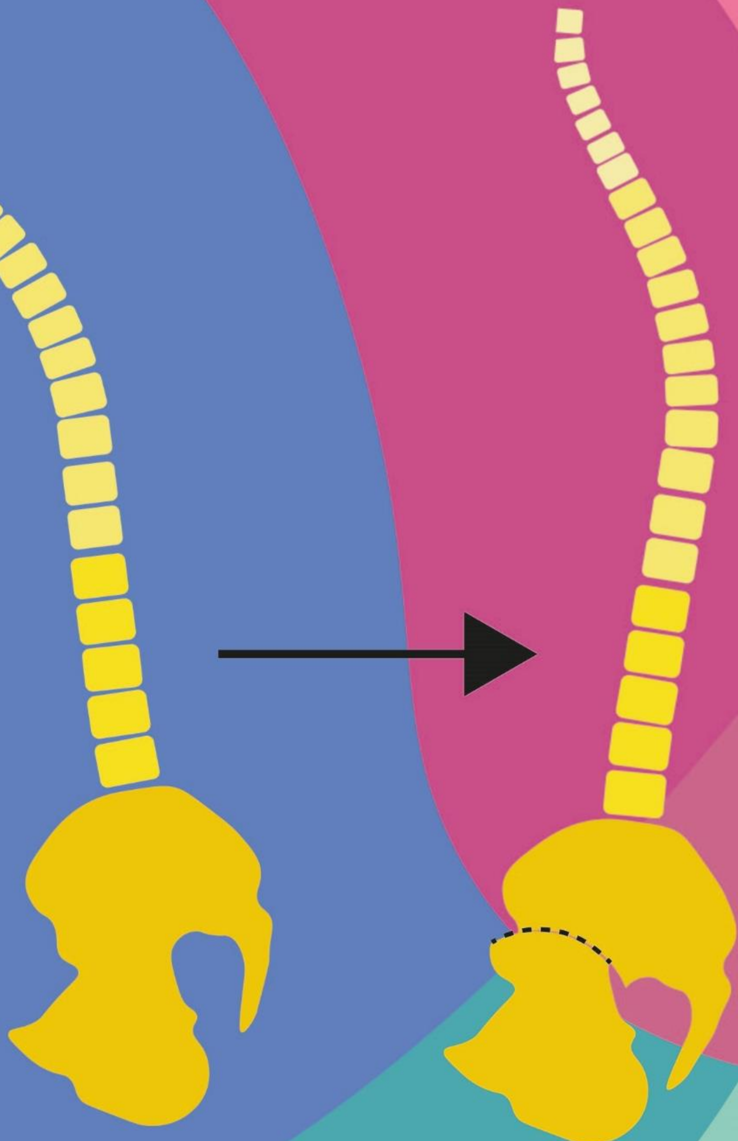
The dome pelvic osteotomy as alternative for pedicle subtraction osteotomy in patients with loss of lumbar lordosis

Master Thesis Technical Medicine



M.L. Claessens
April 2023

Graduation commitee

Prof.dr.ir. C.H. Slump	Chair & Technical supervisor
Prof.dr. M. Kruijt	Medical supervisor
MSc. H.C. Nyugen	Daily supervisor
Drs. P.a. van Katwijk	Process supervisor
Ir. J. Magré	Daily supervisor
Dr.ir. A.M. Leferink	External supervisor

UNIVERSITY OF TWENTE.

UMC Utrecht

Abstract

Introduction The aim of this study was to investigate the possible correction of the pelvic sacral angle (PSA) with a dome pelvis osteotomy (DPO) as alternative for a pedicle subtraction osteotomy (PSO) in patients with loss of lumbar lordosis (LL). **Methods** Three dome pelvic osteotomies were determined: around the sacral endplate (SEDPO), around the sacroiliac joint (SIDPO), and around the acetabulum (ADPO). These three DPO types were performed on 10 human pelves in an in-silico study using Materialise 3-matic 3D modelling software. The ADPO was chosen to be the best and was tested on a saw bone using a patient-specific 3D modelled bilateral saw guide. Before and after the osteotomy, the PSA and bone contact were assessed on CT scans. **Results** The cranial pelvic part was rotated with 20 degrees, resulting in a PSA correction of 20 degrees and a respective mean bone contact of 34% (SD 9%), 28% (SD 10%), and 31% (SD 5%) for the SEDPO, SIDPO, and ADPO. The ADPO on the saw bone test resulted in 4 degrees PSA deviation and 3% bone contact deviation from the planning. **Conclusion** The ADPO proved to be technically effective and practically feasible. A cadaveric study and clinical study are required to determine the anatomical viability and safety in humans. The DPO is regarded as a useful tool in the orthopedic arsenal for spinal alignment surgery based on in-silico and practical tests.

Keywords Dome pelvic osteotomy • loss of lumbar lordosis • sagittal alignment of the spine • 3D-printed • saw guide

Contents

List of abbreviations

LL	Loss of lumbar lordosis
L1	First lumbar vertebra
FBSS	Failed back surgery syndrome
PI	Pelvic incidence
PT	Pelvic tilt
SVA	Sagittal vertical axis
TPA	T1 pelvic angle
ASD	Adult spine deformity
PSO	Pedicle subtraction osteotomy
BEPO	Bilateral extended pelvic osteotomy
DPO	Dome pelvic osteotomy
UMCU	University Medical Centre Utrecht
SEDPO	Dome pelvis osteotomy around the center of the sacral endplate
SIDPO	Dome pelvis osteotomy around the center of the sacroiliac joint
ADPO	Dome pelvis osteotomy around the center of the acetabulum
APP	Anterior pelvic plane
L-ASIS	Right anterior superior iliac spine
R-ASIS	Left anterior superior iliac spine
MPT	Midpoint of the pubic tubercles
SS	Sacral slope
TK	Thoracic kyphosis
PSA	Pubic sacral angle
CTA	Computed tomography angiography
LSM	Least squares method
ITP	Iterative tangential plane

Introduction

Degenerative loss of lumbar lordosis (LL) is a condition where the angle between the endplate of first lumbar vertebra (L1) and the sacrum diminishes.[1] The lumbar spine can flatten due to spinal degeneration such as disc disease or facet arthrosis.[2] The lumbar spine can also flatten as a result of spinal fusion, especially secondary to Harrington rod instrumentation.[3] This is often referred to as postsurgical spine syndrome or failed back surgery syndrome (FBSS).[4,3] The annual incidence of lumbar degenerative spine disease and FBSS is respectively 3.63% and 0.033% worldwide.[5,6]

Loss of LL is associated with chronic low back pain and sagittal malalignment, which is visible in Figure 1.[7,6] This positive sagittal balance is compensated by muscular effort to tilt the pelvis; the pubic bone is moved cranially and the sacrum anteriorly to attain an upright posture and horizontal gaze.[2,8]

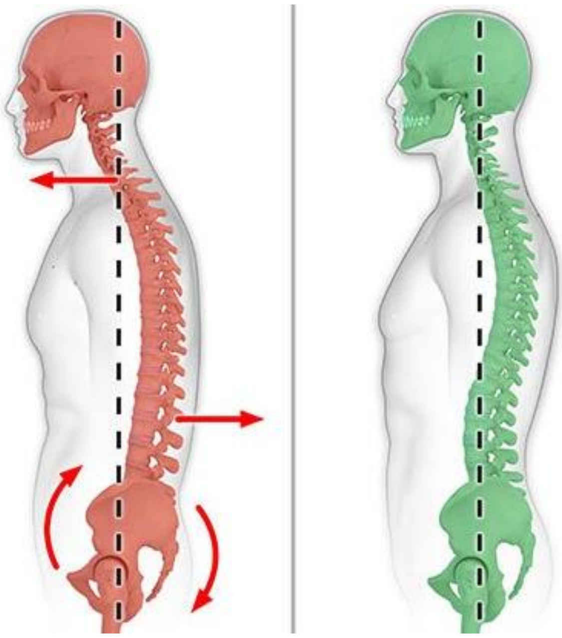


Figure 1. Differences between the a) normal spine and b) spine with degenerative loss of lumbar lordosis.[6]

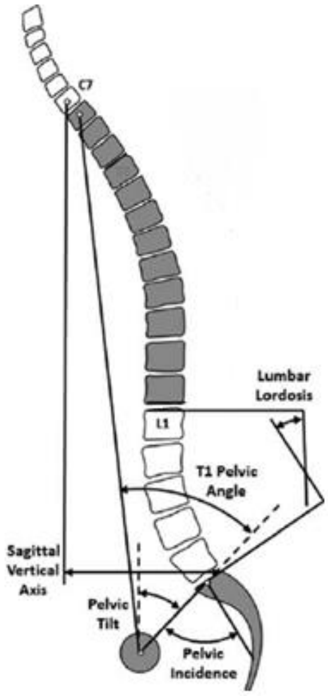


Figure 2. Sagittal spinopelvic radiographic parameters. Visualized are the lumbar lordosis (LL), pelvic incidence (PI), pelvic tilt (PT), sagittal vertical axis (SVA), and T1 pelvic angle (TPA).[1]

To quantify the loss of LL, certain radiographic sagittal spinopelvic parameters are used, which are displayed in Figure 2.[2] LL is the angle between the superior endplate of L1 and the sacrum, which is 60^{o} on average in healthy individuals.[9] The pelvic incidence (PI) is the angle between the plumb line of the sacral endplate and the center point of the femur head. The PI angle is a measure for sagittal spinal alignment.[10] This is 55 degrees (SD 10) in healthy individuals.[2] The sagittal vertical axis (SVA) is drawn downwards from the center of C7, it should be within 5 mm from the superior-posterior point of the sacrum.[11] In patients with loss of LL, the SVA is shifted anteriorly and the distance to the sacrum is more than 5 mm.

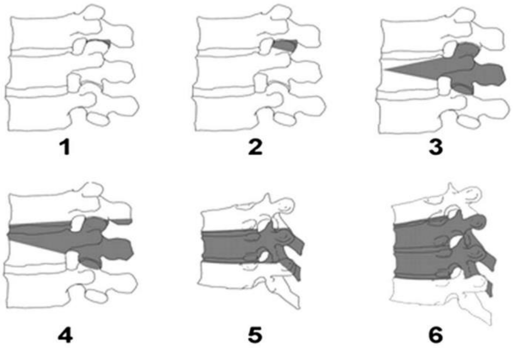


Figure 3. Six osteotomy grades for adult spine deformity (ASD) treatment 1) partial facet joint resection, 2) complete facet joint resection, 3) pedicle and partial body resection, 4) pedicle, partial body, and disc resection, 5) complete vertebra and disc resection, and 6) multiple adjacent vertebrae and disc resection.[12]

Current surgical treatment for sagittal spinal deformity is pedicle subtraction osteotomy (PSO), this is indicated in patients with more than 25 degrees of loss of LL.[13] The PSO aims to restore the SVA and therefore the sagittal alignment of the spine. The PSO can be classified into six types with increasing ability to correct the spinal alignment, which are visualized in Figure 3.[14,12] Complication rate of open adult spine deformity (ASD) surgery is 62.5%.[15] Complications include, but are not limited to: injury to cauda equina, death, injury to nerve root, vascular or visceral injury, adjacent segment degeneration, and proximal junctional kyphosis.[2,15] Additionally, the incidence of pseudoarthrosis in ASD surgery is 6.3%[16] Next to that, PSO is associated with an average blood loss of 2 L.[11] Reoperation in the same region to treat FBSS has shown a success rate of only 35% and a high morbidity rate.[17,11] The success rate of spinal surgery declines with the number of prior spinal surgery to 15% and 5% for third and fourth surgery.[4] Therefore, the goal of this research is to develop a treatment strategy instead of the pedicle subtraction osteotomy that restores the SVA in patients with loss of lumbar lordosis. For that purpose, we aim at a pelvic osteotomy.

A new surgical technique for spinal sagittal malalignment was proposed at the University Medical Centre Utrecht (UMCU). This surgery targets the pelvis rather than the spine to realign the spine in sagittal direction and is called the bilateral extended pelvic osteotomy (BEPO).[15] In this procedure, a variation on the Salter osteotomy is created bilaterally. Contrary to the Salter osteotomy, one centimeter of posterior iliac cortex is left intact.[15] This results in a cranial and caudal pelvis part. Subsequently, the upper part is tilted to decrease the PI with subsequent adjustment of the SVA. This is visualized in Figure 4.

Research regarding this alternative for PSO is ongoing at the UMCU. A cadaver study of the BEPO showed a mean correction of the PI of 10.4 degrees and showed occurrence of bilateral hinge fractures in the posterior iliac cortex at the location of the sciatic nerve foramen.[18] A patient specific wedge implant was recommended to achieve a stable pelvis.[19] The correction after the BEPO is much lower than required as an alternative for e.g. PSO with an correction indication of 25 degrees[20,13] or the average correction that can be achieved in the spine according to Schwab (20-35 degrees).[15,13] Additionally, the feasibility and safety of the BEPO is arguable, due to the chance of posterior hinge fractures. This primed the curiosity about a potential improvement in correction angle and stability with an alternative pelvic osteotomy.

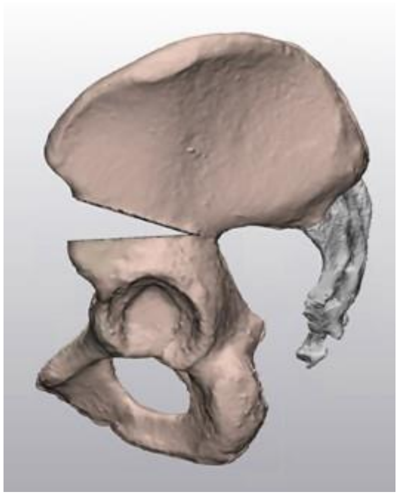


Figure 4. The bilateral extended pelvic osteotomy (BEPO) with angulated cranial pelvic part.

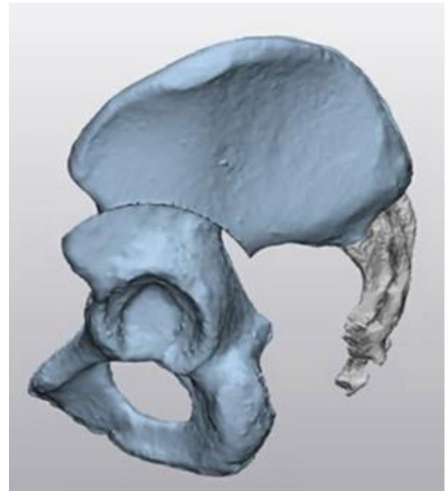


Figure 5. The dome pelvic osteotomy (DPO) with rotated cranial pelvis part.

An alternative for the BEPO has been proposed at the UMCU. This surgery is a variation of the Pemberton periacetabular pelvic osteotomy as first described by Pemberton.[21] It is a dome-shaped osteotomy, that is created bilaterally, proceeding all the way through the ilium towards the sciatic nerve foramen. Subsequently, the cranial part is rotated posteriorly with respect to the caudal part. This procedure will hereafter be referred to as the dome pelvic osteotomy (DPO). Figure 5 shows an example of the DPO.

The hypothesis is that a DPO will be advantageous over a BEPO because

1) there is no risk of posterior hinge fracture, since the DPO divides the ilium in two parts,
2) the bone bone-to-bone contact facilitates stable fusion,
3) a larger correction angle can be achieved by the DPO.

We believe this larger correction can be achieved for two reasons: 1) The cranial pelvis part can be rotated around a point that is the true rotation axis of the spine with respect to the pelvis, rather than around the posterior osteotomy point of the BEPO. 2) A DPO does not result in an opening wedge that destabilizes the pelvis and poses risk fracture, so a larger correction angle might be possible.

The aim of this study is to investigate the feasibility and efficacy of the DPO compared to the PSO and BEPO to adjust the sagittal spinal alignment in patients with loss of lumbar lordosis. Chapter 1 explores three different locations of the DPO. It provides a definition of the pelvic coordinate system, which serves as the basis of the 3D modelling the DPO. It also specifies a universal outcome parameter for sagittal alignment correction. Chapter 2 studies the difference between the three different DPO locations in sagittal alignment adjustment of the spine and bone contact of the cranial and caudal pelvis part in-silico. These results are compared with the PSO and the BEPO. Based on the in-silico results, the best type of DPO was chosen in a panel meeting with two orthopedic surgeons. Chapter 3 investigates the technical feasibility of the chosen DPO using a lateral surgical approach and a 3D printed saw guide in a saw bone study. Finally, Chapter 4 addresses future steps needed to implement the ADPO clinically.

1. Fundamental work

1.1 Defining dome pelvic osteotomy locations

The possible locations of the DPO were first evaluated. The DPO location is where the dome osteotomy's center point is located. We considered 1) the natural rotation axis of the spine with respect to the pelvis and 2) the feasibility of the surgical approach and procedure to determine the DPO locations. The pelvic incidence angle is measured from the center of the sacral endplate. Therefore, we hypothesized that performing the DPO and rotating the pelvis around this point, would change the PI. Since the PI angle is a measure for sagittal spinal alignment[10], this would directly change the sagittal alignment of the spine. The second location is the sacroiliac joint. Because this is the location where the spine theoretically rotates with respect to the pelvis, if the sacroiliac joint was not as stiff as it is. The third location is the acetabulum center, as this provides the functional rotation of upper body with respect to the lower body by pelvic tilt. This is also known as an accessible location to perform a pelvic osteotomy, since multiple periacetabular osteotomies, such as the Pemberton and Chiari osteotomy are performed here.[22,23,24]

Hence, three DPOs were defined to adjust the sagittal alignment of the spine, as visualized in Figure 6:

1) around the center of the sacral endplate (SEDPO),
2) around the center of the sacroiliac joint (SIDPO),
3) around the center of the acetabulum (ADPO).

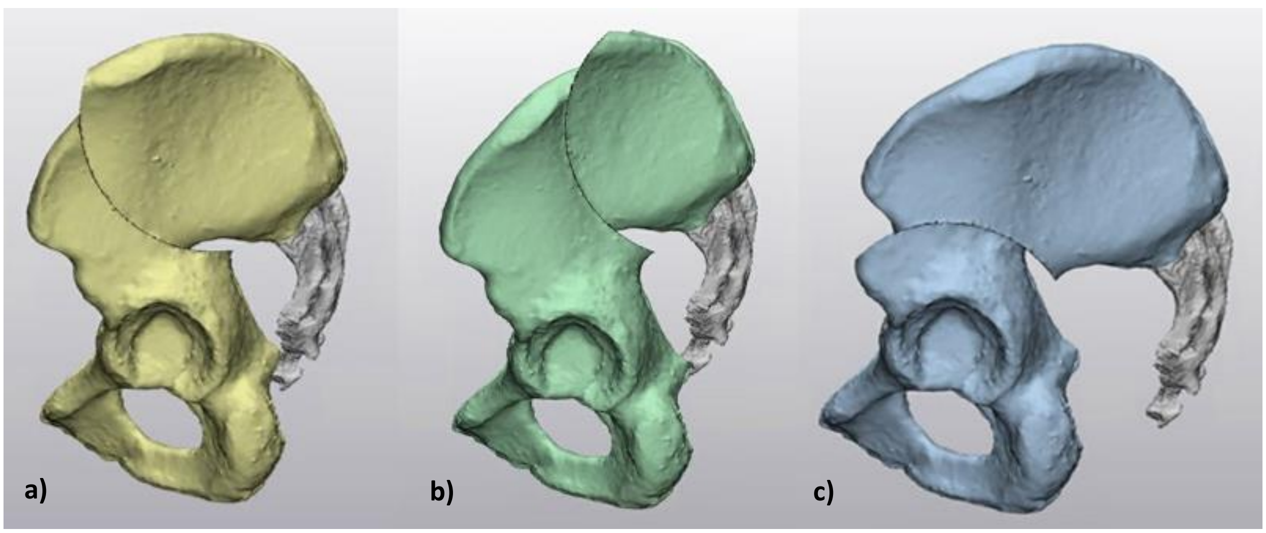
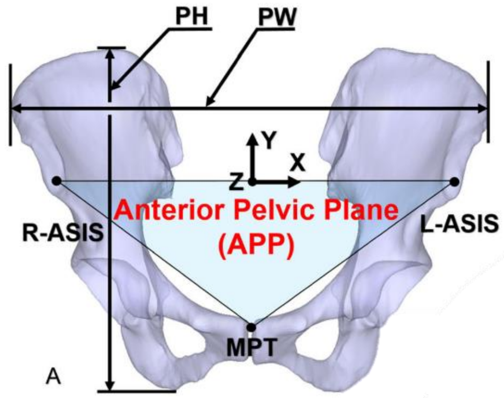


Figure 6. Three pelvic dome osteotomy techniques: a) around the center of the sacral endplate (SEDPO) b around the center of the sacroiliac joint (SIDPO), and c) around the center of the acetabulum (ADPO).

1.2 Defining coordinate system

A pelvic coordinate system was needed to reproducibly 3D model the DPO planning. A robust pelvic coordinate system defined by the bony landmarks on the pelvis is the anterior pelvic plane (APP) coordinate system, this is visible in Figure 7a. The sagittal plane is defined by a plane perpendicular to the APP and through the center point, the midpoint between the right and left anterior superior iliac spine (ASIS), and the midpoint of the tubercles (MPT). The axial plane is defined perpendicular to the APP and the sagittal plane through the center of the coordinate system. The APP, sagittal, and axial plane together create the APP coordinate system, as is visible in Figure 7b.

The APP is a commonly used coordinate system when measuring angles in the dysplastic hips[25] and defining acetabular component orientation in total hip replacements[26,27]. We speculate that the anatomic landmarks are pronounced and can therefore be reproducibly selected on pelvic CT scans, ensuring a robust method to define a pelvic coordinate system.



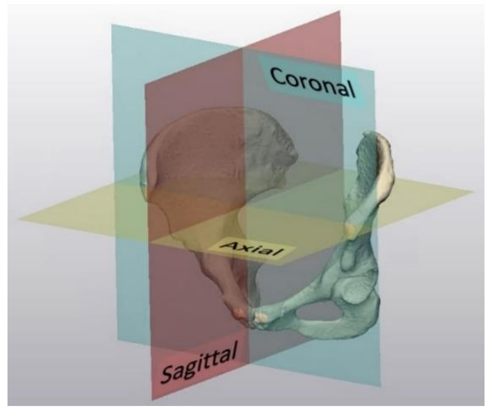


Figure 7. a) The anatomic landmarks: right anterior superior iliac spine (R-ASIS), left anterior superior iliac spine (L-ASIS), and the midpoint of the pubic tubercles (MPT) that define the anterior pelvic plane (APP), and the center of the coordinate system.[25] The z-axis is directed towards posterior. b) The coronal, sagittal, and axial plane of the coordinate system.[26]

1.3 Defining a universal outcome parameter for sagittal alignment correction

An outcome parameter was needed to quantify the change in sagittal balance of the spine with respect to the pelvis after a DPO. Such a parameter must meet four requirements, it must be:

1) independent of the position of the patient,
2) related to the rotation angle of the cranial part relative to the caudal part,
3) measurable in a robust way,
4) related to the sagittal balance of the spine.

Recent literature about sagittal spinal balance classification and correction using a pelvic osteotomy uses the PI to quantify the change in sagittal balance.[18,28,29,30,31] Therefore, this parameter was considered as outcome parameter. The PI is defined by a line perpendicular to the sacral endplate center and a line from the center of the sacral endplate to the line between the two acetabulum centers, as is visualized in Figure 8a. The PI is independent of the orientation of the pelvis[32]. Next to that, the bony landmarks that compose the PI are evident and can therefore be identified robustly. Additionally, the PI is shown to be strongly correlated with pelvic tilt (PT)[10,33] and sacral slope (SS)[10,29,33,32], following formula (1). These pelvic parameters, in turn, determine the lumbar lordosis[29] and thoracic kyphosis (TK)[28,34]; the sagittal balance of the spine. following formula (2). Therefore, the PI is related to the sagittal balance of the spine.

$$PI = PT + SS \tag{1}$$

$$TK = 2 \times (PT + LL - PI) \tag{2}$$

However, the PI does not meet the second requirement; the PI does not change when the cranial part is rotated around the caudal part after an ADPO, as is shown in Figure 8b. This is also shown by Roussouly et al.; the Chiari osteotomy, which is comparable to our ADPO, did not show a change in PI angle.[30]

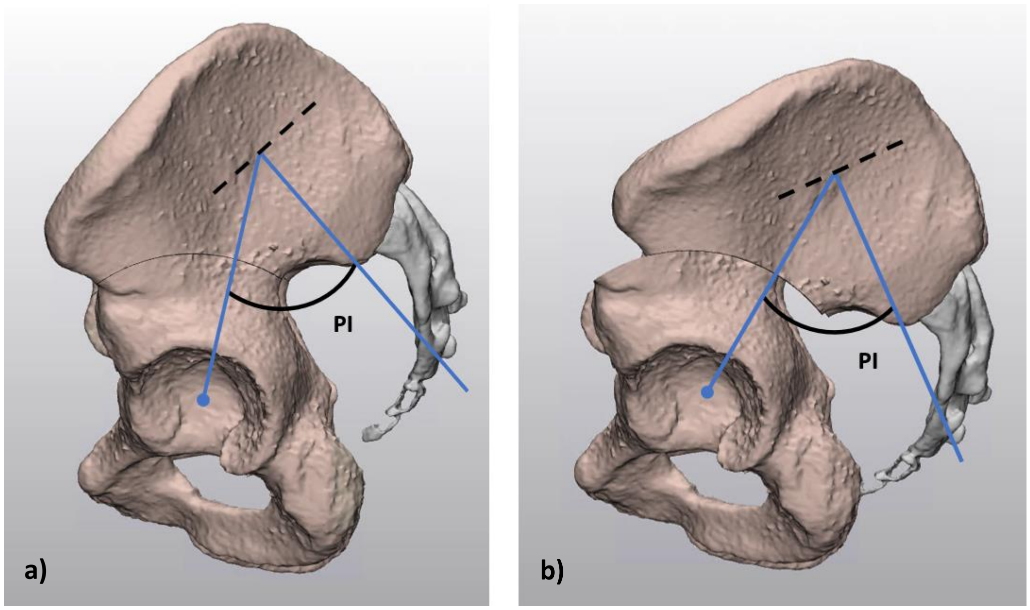


Figure 8. PI measurement a) before and b) after the periacetabular dome osteotomy resulting in the same PI angle.

There are two reasons for this: first, the lines defining the PI angle, are divided by the osteotomy and second, one of the points that defines the PI, functions as a rotation point for the cranial pelvis part. This causes the PI to remain unchanged, because the two lines that define the PI, do not change with respect to each other. Similarly, the anterior plane line in relation to the sacral endplate cannot be used as it is intersected by the osteotomy. The three osteotomy lines and a line from the sacral endplate to the APP are visualized in Figure 9.

A line where one point is the same as the rotation point of the ADPO would work, as long as this line is not intersected by the osteotomy. Therefore, we propose a universal angle that changes when the cranial part is rotated relative to the caudal part; the pubic sacral angle (PSA). This is defined as the angle between two lines: 1) the line connecting the left pubic tubercule and the left acetabulum center, located below the osteotomy line, and 2) a line perpendicular to the center of the sacral endplate in the sagittal plane, similar to posterior line of the PI, which is located above the osteotomy line. The PSA is visualized in Figure 10.

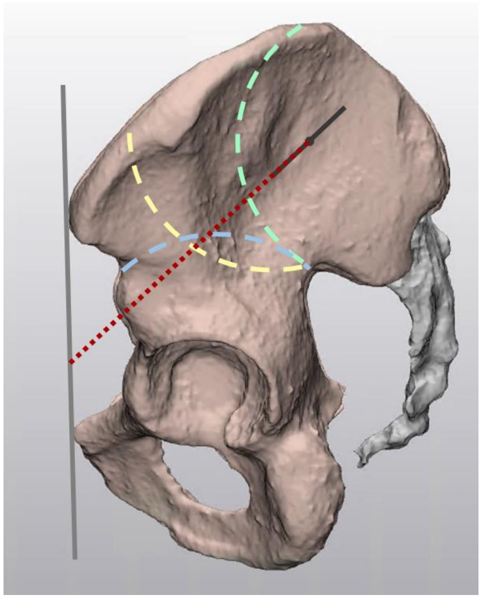


Figure 9. Osteotomy lines of the SEDPO (yellow), SIDPO (green), ADPO (blue), the APP (grey), sacral endplate (black), and a line from the sacral endplate to the APP (red).

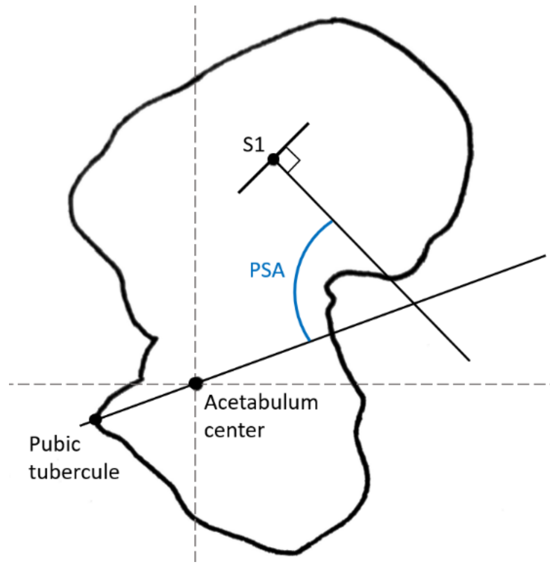


Figure 10. Schematic depiction of the pubic sacral angle (PSA), the angle between the pubic tubercule, the center of the acetabulum, and the center of the sacral endplate.

This PSA meets all four requirements to quantify the change in sagittal balance after a PDO. First, it is independent of the position of the patient.[32] Second, the PSA changes similar to the rotation of the cranial part of the dome osteotomy, following formula (3). Here, β is the rotation angle of the cranial pelvis part relative to the caudal pelvic part. Third, the sacral endplate center, pubic tubercule, and acetabulum center are distinct, so these landmarks can be identified robustly. Fourth, the PSA is related to the sacral slope, following formula (4). Here α is the angle of the lower line of the PSA angle and the vertical, as is elucidated in Appendix A. As was shown above by formula (1) and (2), the SS is a measure for the spinal sagittal balance. Therefore, formula (4) shows that the PSA is related to the sagittal balance of the spine.

$$\Delta PSA = \beta \tag{3}$$

$$PSA = 180 - SS - \alpha \tag{4}$$

The derivation of these formulas can be found in appendix A.

2. In-silico study

The three DPO types were performed on ten healthy subjects in an in-silico study to gain knowledge on the feasibility of the DPO. Both the technical feasibility and the anatomical feasibility were studied. Five outcome measures with requirements were set, this is shown in Table 1. The minimum PSA angle requirement was based on the results of the BEPO study, that showed maximum a correction of 15 degrees.[18] The goal was to realize more correction with the DPO than with the BEPO. The minimal bone contact needed for stable fixation and eventually bone union was hypothesized to be 25%, since no literature was available on the minimum needed bone contact.

Table 1. Outcome measures and requirements of the in-silico study.

Outcome measure	**Requirement**
Technical feasibility	
1. PSA	Must be at least 15 degrees.
2. Bone contact	Must be at least 25%.
Anatomical feasibility	
3. Sciatic nerve manipulation	Must not be compressed.
4. Sacrum translation	Should translate relative to the APP as little as possible.
5. Surgical approach	Must be possible.

The in-silico study exactly quantifies the technical feasibility; the effect of the DPO on the sagittal alignment (the ΔPSA) and the remaining bone contact. The in-silico study approximates the anatomical feasibility, since this can only be properly researched in a test setup that represents the anatomic features, such as a cadaver test. The most feasible of the three DPO types was chosen in a panel meeting with two orthopedic surgeons with 10 and 30 years of experience. This DPO type will be used in the saw bone test. The protocol of the in-silico study is visualized in Figure 11.

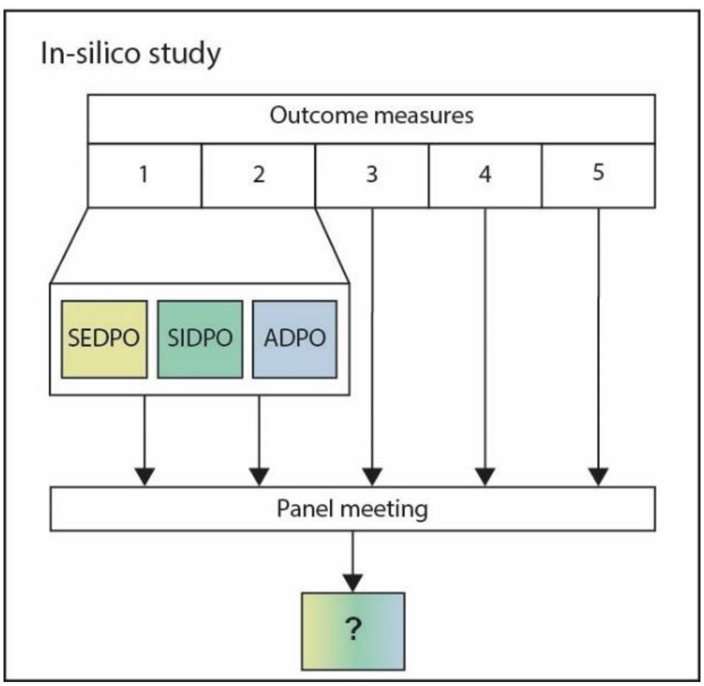


Figure 11. Schematic overview of the in-silico study.

The choice was made to develop one standard treatment that can be used in all patients, rather than further develop the SEDPO, SIDPO, and ADPO to create a patient specific treatment. In a patient specific treatment, all three DPO types would be planned for one patient. The DPO yielding the most bone contact would be chosen for that patient. In a standard treatment, however, the DPO chosen in the in-silico study would be used in every eligible patient. This ensures fast growing experience with this osteotomy and therefore a safer procedure. We think this extra safety of a standard treatment outweighs the benefit of a larger bone contact that the patient specific treatment can provide in some patients.

2.1 Methods

2.1.1 Data preparation

Ten computed tomography angiography (CTA) scans were selected from an existing anonymized database with thirty CTA scans. The inclusion criteria in descending order of importance, were:

- no history of pelvic or hip fractures,
- largest possible distribution in PI,
- largest possible distribution in age,
- the female:male ratio should be 1:1.

The data set consisted of 5 male and 5 female patients, with a mean age 27 years old (SD 5) and a mean PI of 56 degrees (SD 14). All CTA scans included the whole pelvis and had a slice thickness of 0.9 mm. None of the subjects had any history of pelvic fractures, hip fractures, or surgery. The patients approved usage of these scans for research purposes. The Medical Ethical Committee judged the data not to be subject to the Medical Research Involving Human Subjects Act (WMO), according to IRB Protocol 16-612/C. The pelves and sacrums were segmented using Materialise Mimics 24.0 (Materialise, Leuven, Belgium). In five pelves, the sciatic nerve was segmented by marking the nerve location in 10 slices using Materialise Mimics 24.0.

2.1.2 In-silico surgical procedure

The three dome pelvic osteotomies; 1) the SEDPO, 2) the SIDPO, and 3) the ADPO were modeled on every pelvis using Materialise 3-matic 16.0 (Materialise, Leuven, Belgium). Cylinders were used to model the osteotomies, with cylinder's mantle serving as the osteotomy cutplane. The direction of these cylinders was parallel to the x-axis of the APP. The locations of these cylinders were 1) the center of the sacral endplate, 2) the center of the sacroiliac joint, and 3) the center of the left acetabulum. Depending on the type of osteotomy used, the cylinder's diameter was adjusted until the cylinder intersected the iliac cortex anteriorly and posteriorly. The SEDPO and SIDPO cylinders intersect the ilium at respectively 3 mm and 6 mm distance from the ASIS anteriorly and in the center of the great sciatic notch posteriorly. The ADPO cylinder intersects the pelvis between the ASIS and AIIS anteriorly and in the center of the great sciatic notch posteriorly. This is visualized in Figure 12a. The sciatic nerve markings were imported in Materialise 3-matic 16.0 and the nerves were reconstructed. This is visualized in Figure 12b.

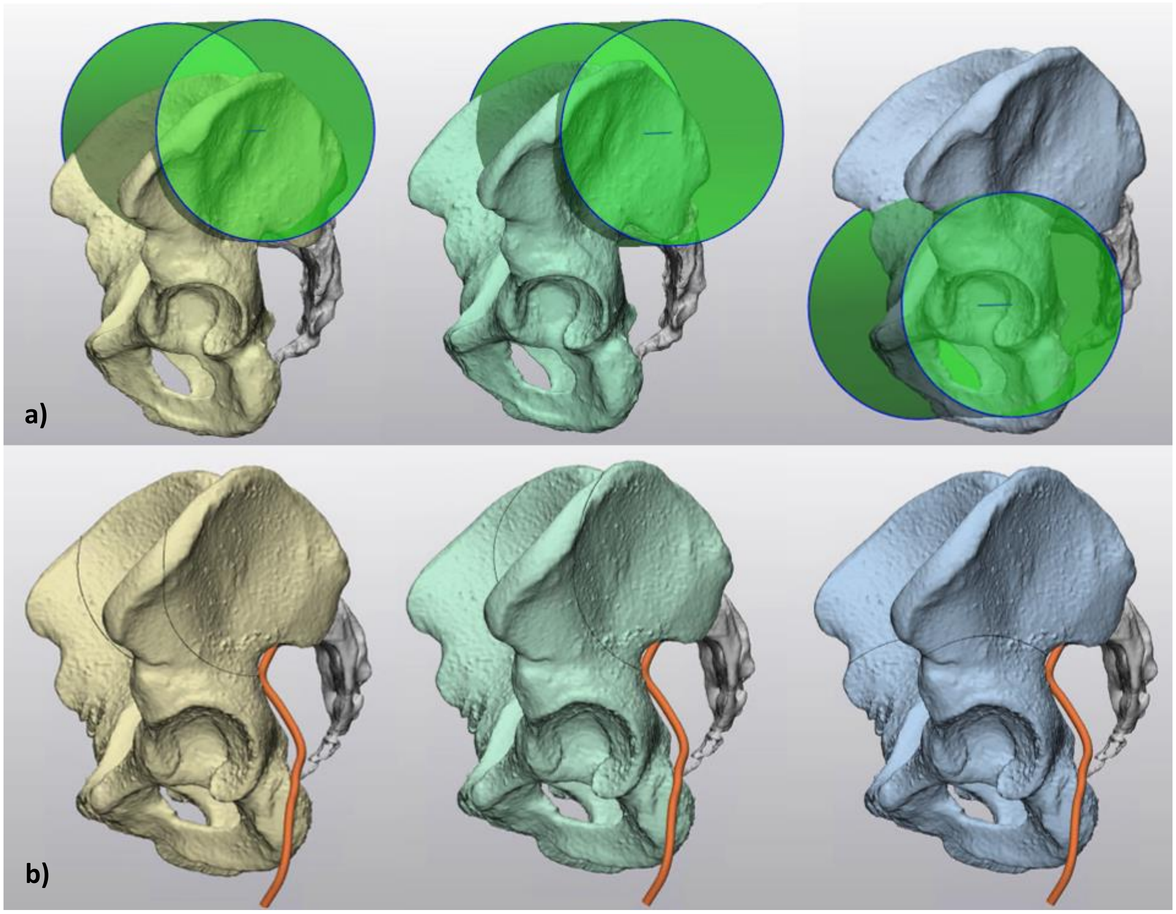


Figure 12. a) The osteotomy cylinders (bright green) and b) the sciatic nerve (orange) reconstruction for the SEDPO (yellow), SIDPO (green), and ADPO (blue).

The cylinders were carefully positioned to prevent intersection of the acetabulum roof and the origo of the sartorius muscle. Using Materialise 3-matic 16.0, each osteotomy type was carried out by dissecting the ilium along the cylinder surface, beginning at the iliac crest or iliac spine and ending at the sciatic foramen. This divided the pelvis in two parts: the cranial and caudal part. The cranial part was rotated relative to the caudal part with 10, 15, and 20 degrees.

2.1.3 Data analysis

The PSA was measured in the sagittal plane of the APP after the osteotomy. The PSA was measured in the preoperative position (0 degrees rotation) and after a rotation of the cranial part of 10, 15, and 20 degrees, resulting in four angle measurements. The cut surface and the bone contact surface of the ilium parts were also measured after rotation of 0, 10, 15, and 20 degrees. The contact surface relative to the osteotomy surface is calculated using formula (6).

$$Bone\ contact\ (\%) = \frac{bone\ contact\ surface\ of\ ilium\ parts\ (mm^2)}{bone\ surface\ at\ osteotomy\ surface\ (mm^2)} \times 100 \qquad (6)$$

To verify a linear relation between the bone contact percentage and the rotation angle, the least squares method (LSM) was used.[35] This method minimizes the sum of squares of errors (the variance), to create a line of fit. This results in a regression line with the least vertical distance from the data points. For each DPO type, a line was fitted through the mean bone contact percentages of 0, 10, 15, and 20 degrees rotation, yielding 3 fitted lines. R^2 is the coefficient of correlation, an R^2 of 1.0 indicates a perfect fit, an R^2 lower than 0.5 indicates a bad fit. Both the execution of the osteotomies and the measurement of the PSA and the bone contact was automated by a custom script that was generated using the scripting module of Materialise 3-matic.

2.2 Results

The relation between the rotation angle and the change in PSA (correction angle) was 1:1 for every DPO type (SEDPO, SIDPO, and ADPO). Figure 13 shows the pelvis and sacrum after the SEDPO, SIDPO, and ADPO. The mean bone contact of the SEDPO, SIDPO, and ADPO was respectively 34% (SD 9%), 28% (SD 10%), and 31% (SD 5%) after a rotation of 20 degrees. The SEDPO shows a significantly larger bone contact than the SIDPO after a rotation of 20 degrees. However, the two-sided, coupled T-test shows no significant difference with the bone contact of the ADPO after a rotation of 20 degrees.

On the other hand, the ADPO showed the smallest deviation of bone contact, as can be seen in Figure 14. Additionally, after a rotation angle of 20 angle of 20 degrees the bone contact of the ADPO was higher than 25% for all pelves. Therefore, the ADPO met requirements #1 and #2 for every pelvis, this is shown in Table 2. The LSM fit in Figure 14 shows the trendline through the mean bone contact percentages of rotation angles 0, 10, 15, and 20 degrees, for each DPO type. Each LSM fit had an R2 larger than 0.99. This a linear correlation of the PSA and the bone contact.

The sciatic nerve compression, sacrum translation and surgical approach were discussed in the panel meeting. Figure 15 illustrates how the translation of the sacrum towards the APP was the smallest after the ADPO. The distance between the sciatic nerve and the osteotomy was the largest after the ADPO. This indicates that no sciatic nerve compression would occur after the DPO, while the SEDPO and SIDPO could result in nerve compression. Therefore, only the ADPO complied with requirements #3 and #4. The surgical approach of the ADPO was preferred, because this osteotomy can be performed via an anterior approach while the patient is positioned supine, similar to the Pemberton and Chiari osteotomy. For the SEDPO and SIDPO there is no experience and therefore no data on the possibility of the approach. Hence, only the ADPO complied with requirement #5, this is shown in Table 2. Altogether, the panel meeting decided to continue with the ADPO.

Table 2. Compliance of the SEDPO, SIDPO, and ADPO with the requirements for the technical and anatomical outcome measures.

Outcome measure	SEDPO	SIDPO	ADPO
A. Technical feasibility			
1. PSA > 15 degrees	✓	✓	✓
2. Bone contact > 25%	✕	✕	✓
B. Anatomical feasibility			
3. No sciatic nerve compression	✕	✕	✓
4. Minimal sacrum translation	✕	✕	✓
5. Possible surgical approach	✓	✓	✓

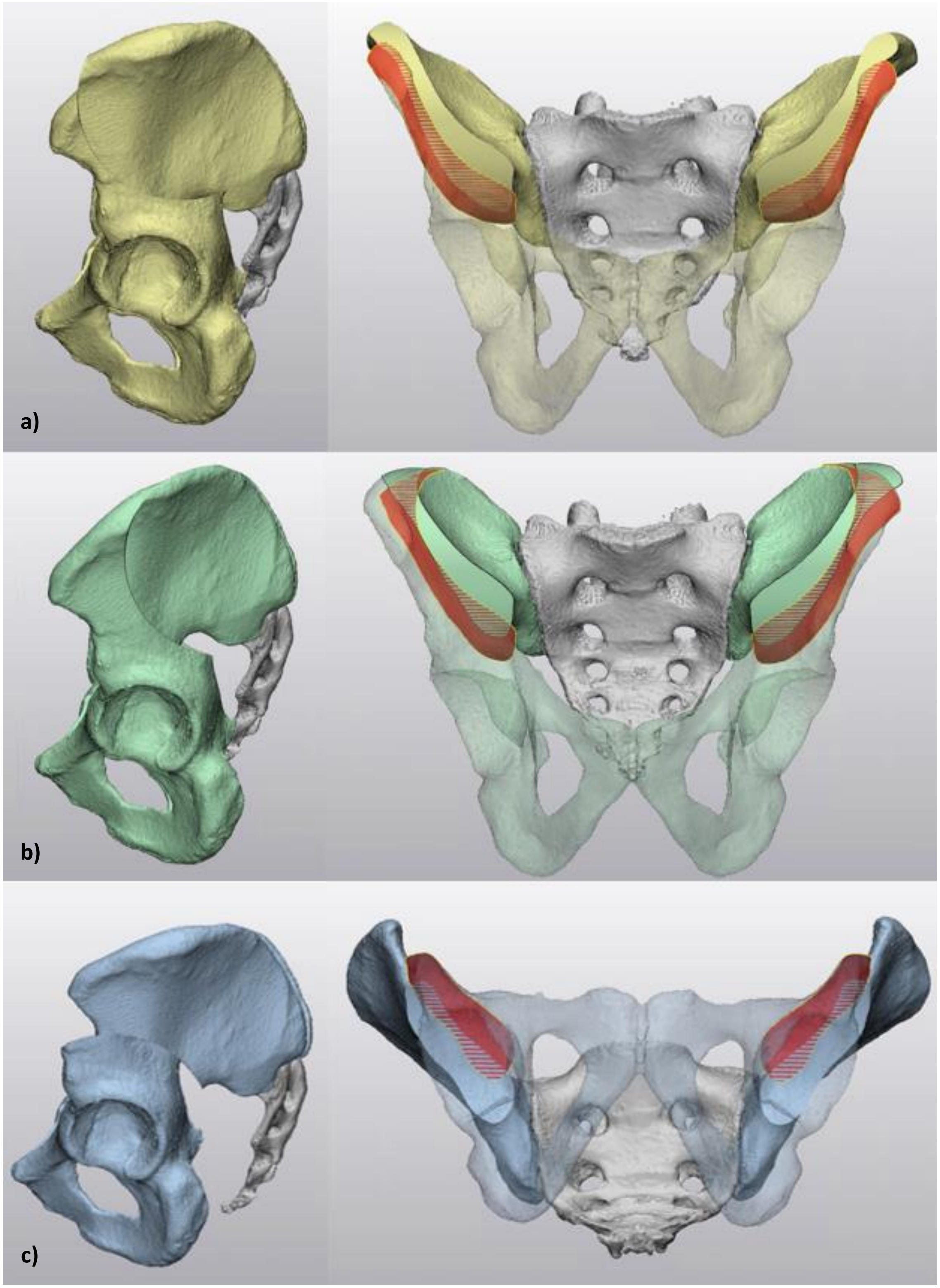


Figure 13. From top to bottom: Lateral and caudal view of the a) SEDPO (yellow), b) SIDPO (green), and c) ADPO (blue) after cranial part rotation of 20 degrees. The bone contact between the pelvic parts is visualized in striped red, the non-contact cut surface is visualized in solid red.

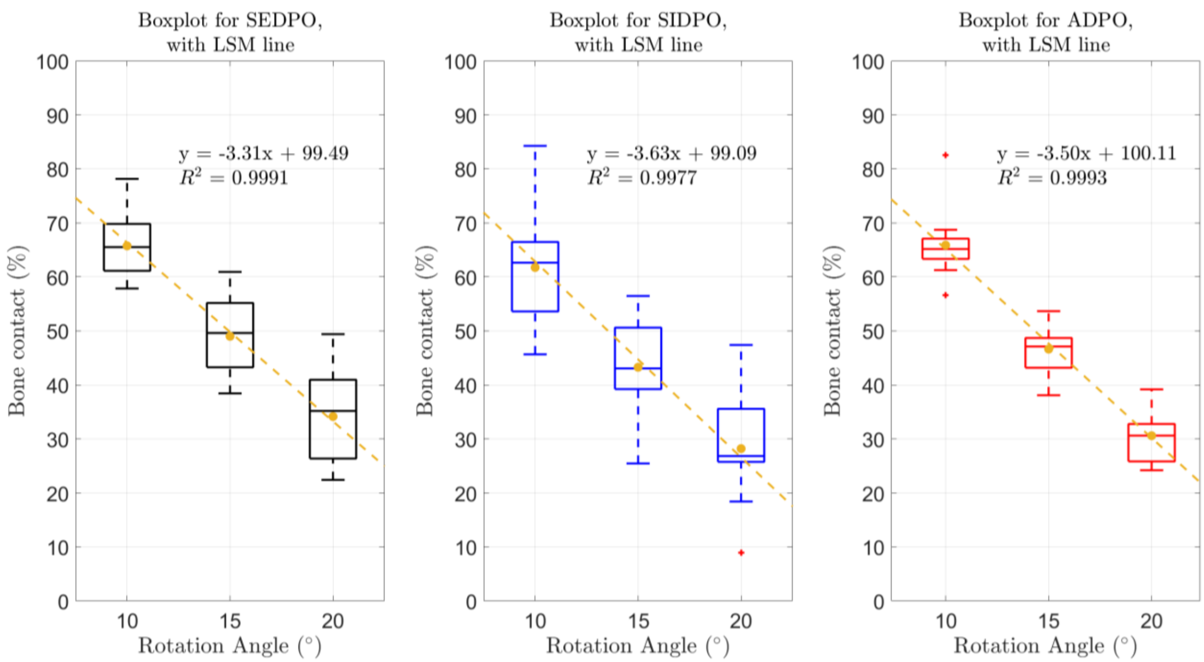


Figure 14. Boxplot of the bone contact percentage for rotation angles 0, 10, 15, and 20 degrees after the SEDPO (black), SIDPO (blue), and ADPO (red) with the mean least squares fitted line through the mean bone contact (yellow).

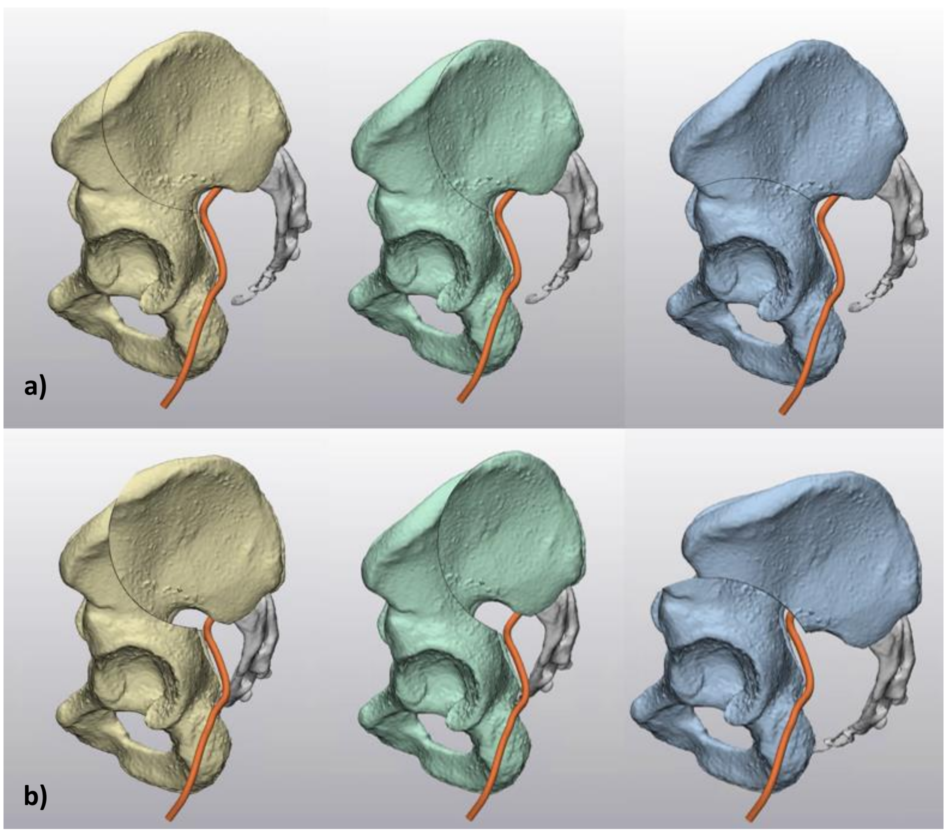


Figure 15. Sciatic nerve and sacrum position in one patient a) before and b) after the SEDPO (yellow), SIDPO (green), and ADPO (blue).

2.3 Discussion

2.3.1 Interpretation

Two articles were found that use a similar technique to perform a pelvic osteotomy for sagittal alignment correction.[18,30] Ochtman et al. tested the BEPO in 10 cadavers. The BEPO resulted in a mean change in PI angle of 10 degrees. Since we employed the PSA as an outcome measure, this cannot be compared with the correction of the ADPO. Appendix E provides a thorough comparison of the BEPO, SEDPO, SIDPO, and ADPO.[36] Roussouly et al. simulated four pelvic osteotomies on 15 scans of pelvic bones in the software Surgimap® (Nemaris Inc., New York, NY, USA). A Chiari osteotomy, which is similar to our ADPO, resulted as expected in a minimal mean difference in PI angle of 1 degree after rotating 10 degrees. They also simulated a PSO around the sacral endplate, which is comparable to our SEDPO and SIDPO. This resulted in a mean difference in PI angle of 20 degrees for a rotation of 20 degrees.

2.3.2 Limitations

The first limitation is the age difference between the study population and the possible patient population. The pelves used in the in-silico study were of healthy subjects, aged between 21 and 35 years. The population suffering from adult spinal deformity and resulting sagittal malalignment typically is 65 years and older.[37] Age should not be a concern for the PI, since the PI does not change much after growth.[38] However, because of the age difference, it is anticipated that the bone porosity of the patient population would differ from that of this research. This could have impaired the ability to identify bony pelvis landmarks. Kuchař, Henyš, Retjar et al. automated the prediction of pelvic bone landmarks in a population of 200 individuals with mean age 64 (SD 13.5 year). They found that the errors between the automated and manual predicted landmarks were within millimeters. Therefore, it is thought that the capacity to identify the bony pelvis landmarks is unaffected by age. Moreover, Trobish et al. studied the risk factors for LL in 417 patients aged 18 and younger who underwent idiopathic scoliosis surgery.[39] A comparable research was carried out by Li et al. in 69 individuals with a mean age of 58.4 years.[40] In both studies, there was no significant difference in PI between the patients who developed LL and those who did not.[39,40] Consequently, it is assumed that age has no influence on the findings of this study regarding correction angle and bone contact.

The second limitation is the possible difference between the subjects and the patient population. The included subjects were younger, in good health, and had no history of spine surgery, loss of lumbar lordosis or sagittal malalignment. However, the pelvis of the patient population might have a different PI as a confounding risk factor for sagittal imbalance. Li et al. reported a significantly larger PI in patients who lost lumbar lordosis after idiopathic scoliosis surgery.[40] Patients with LL (n=37) had a mean PI of 58.38^{o} (SD 9.13) and patients without LL (n=32) had a mean PI of 53.16 degrees (SD 8.25). Trobish et al. however, did not find a statistically significant difference in PI between patients who developed LL as a consequence of idiopathic scoliosis surgery and those who did not.[39] The PI of a patient population was also reported by Roussouly et al.[30]. In this study, eleven patients with LL were included to undergo a pelvic osteotomy, they had a mean PI of 60 degrees (SD 12.1). Our healthy study population had a mean PI of 60 degrees (SD 12.9), which is similar to the LL patient population of Roussouly et al. and Li et al.. Therefore, it is thought that our study population is a good representation of the patient population regarding the PI. Accordingly, it is expected that the choice for the ADPO will hold in a larger study population.

The third limitation of this project is the included sample size. The CTA scans of ten patients were included. This may have caused an under- or overrepresentation of outlier pelvic shapes, sizes or other contributing factors. Because of this, it may be impossible to extrapolate the conclusions about bone contact to the entire patient population, therefore the results on bone contact should be interpreted carefully.

2.3.3 Recommendations

The first recommendation is to conduct an in-silico study in which patients who suffer from LL are included. For this study a total of 31 pelves should be included in order to achieve a 95% confidence level and tolerate a 2% margin of error.[41] This ensures a better representation of the pelvis size, PI, and age of the patient population. As a result, it is possible to more accurately generalize the correction angle and bone contact achieved by the three DPO types.

The second important addition to the in-silico study is to quantify the change in position of the sacrum with respect to the pubis. Sacrum position changes during a DPO, which may lead to sigmoid or uterus compression. An indicator for the change in position of the sacrum is the change in length of the sacrospinous and sacrotuberous ligaments. Another way to quantify the change in sacrum position would be to measure the change in distance between the most caudal point of the coccyx to the pubis symphysis. By measuring these variables, a more accurate differentiation between the SEDPO, SIDPO, and ADPO can be made regarding the change in sacrum position.

The third recommendation is to evaluate the change in position or manipulation of the sciatic nerve more elaborately in a cadaver test. This study attempts to objectify a stretch or compression of the sciatic nerve. To this end, the sciatic nerve was segmented and observed after rotation of the pelvic parts. This does not give an accurate depiction of the behavior or manipulation of the nerve following the DPO, since the nerve is rigid in this case. In a cadaver study, the behavior of the nerve can be observed more accurately, which enables an informed choice for the DPO regarding the risk for the sciatic nerve.

The final recommendation is to investigate the lengthening and shortening of the muscles that attach to the pelvis and femur, as the gluteus muscles and the piriformis muscle are expected to shorten, while the rectus femoris, sartorius, iliopsoas muscles are expected to stretch. A possible way to study this, is to segment the right and left femur, as well as the pelvis and sacrum and measure the distance of each muscle orgin on the pelvis to the insertion on the femur before and after the correction DPO. This corresponds to the change in length of these muscles. These lengths need to be compared to literature to investigate if the rectus femoris, sartorius, iliopsoas muscles can adapt to this change in length.

2.3.4 Conclusion

The in-silico test shows the ADPO is a feasible alternative for the PSO in correction of the sagittal alignment of the spine. The ADPO leaves the sciatic nerve and the pelvic floor uncompromised and leaves enough bone contact for a stable fixation of the pelvis. The ADPO can be performed via an anterior approach, which is shown to be possible for the Pemberton and Chiari osteotomy. The ADPO resulted in 31% bone contact, which is regarded enough for stable fixation of the pelvis and eventually bone union. Additionally, the ADPO is an effective alternative for the PSO. It was able to correct the sagittal balance with 20 degrees, which is similar to the lower limit of the possible correction with a PSO (ranging from 20 to 35 degrees).[15,13] All in all, the DPO showed to be a technically feasible and effective alternative for the PSO.

3. Saw bone test

To test the practical feasibility of the ADPO, the ADPO was tested on a saw bone. An asymmetric cut could lead to compression or contraction of the sacrum. An incorrect saw cut shape could result in an erroneous rotation of the pelvic parts, in turn resulting in a deviation of the correction angle or bone contact from the planning. Hence, it is of utmost importance that the saw cut does not deviate from the planning. Therefore, a saw guide was designed to ensure a symmetric dome-shaped saw cut of both the right and left ilium along the perimeter of a virtually defined cylinder. An additional k-wire guide was designed to enable an accurate rotation of the pelvic parts with 20 degrees.

3.1 Methods

The methods of the saw bone test consisted of the design and fabrication of the saw guide, the execution of the test and the analysis. The saw guide design included a literature review of currently used, patient-specific pelvic saw guides, composing the saw guide requirements and the development of the saw guide. Figure 16 gives a schematic overview of the saw bone test methods.

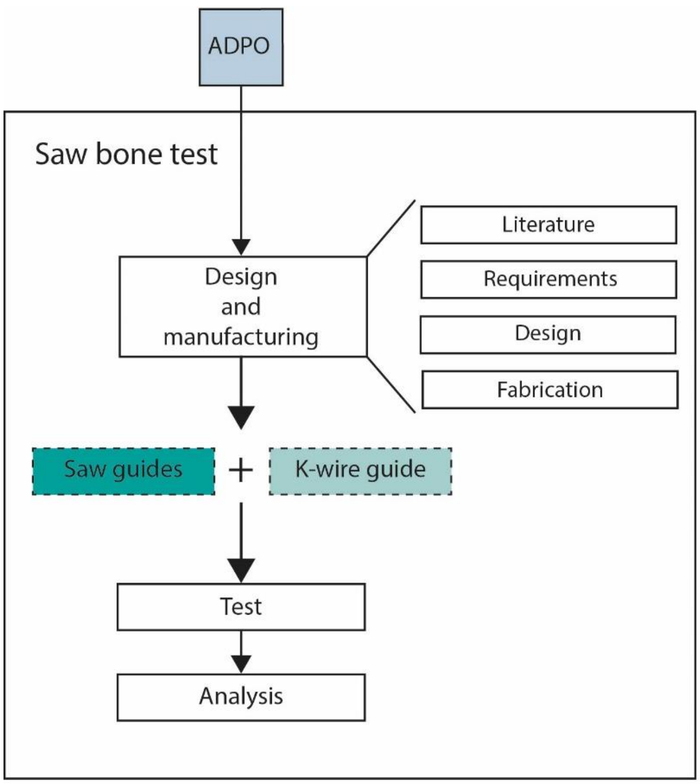


Figure 16. Schematic overview of the saw bone test.

3.1.1 Design and manufacturing

First, a literature review was performed about the state of the art of pelvic saw guides. In bone tumor resection cases, lateral, [42,43,44,45] medial[46,47], and anterior saw guides[48] were designed and clinically used. These are enumerated in Table 3. An elaborate overview of the saw guides found in literature, can be found in Appendix B.

Table 3. Overview of the pelvis saw guides found in literature.

Saw guide	Surgical approach	Guiding principle
Ilium saw guide	Lateral	Support beam[42]
Trans-acetabulum saw guide	Lateral	Slit with small contact surface[43]
Ilium saw guide	Lateral	Slit with large contact surface[44]
Ilium saw guide	Lateral	Slit with large contact surface[45]
Peri-acetabular saw guide	Medial	Slit with small contact surface[46]
Peri-acetabular saw guide	Medial	Support block[47]
Ilium saw guide	Anterior	Directional slit[48]

The medial approach does not provide enough space for the saw to enter the ilium in the posterior part, making it impossible to execute the DPO. Additionally, the guide will be manufactured from nylon using additive manufacturing. The anterior approach would require a guiding slot or block that bends an oscillating saw in the anterior-posterior direction. Since the saw is harder than nylon, the guide will be pierced by the saw, instead of guiding it. Therefore, the anterior saw guide was eliminated, and the lateral guide concept was developed. Second, design requirements were composed for the design of the saw guide and the k-wire guide, these are enumerated in Table 4.

Table 4. Design requirements of the saw guide and caudal k-wire guide.

Part	Requirement
Saw guide	A unique placement of one guide on the ilium must be achievable in under 1 minute
	Must facilitate sawing of the total width of the ilium, measuring 91 mm
	Must support a 50x1.2x0.7 mm reciprocating saw blade
	Must have three holes of 1.9mm diameter with a tolerance of -0.1 and + 0.4mm[49] to allow fixation with 1.8mm k-wires
	Must leave the gluteus maximus, gluteus medius, tensor fascia latae, sartorius, and rectus femoris muscle attachments uncovered
	Must have a label to specify the side and orientation of the guide
	The right saw guide must have an indicator to verify the rotation angle
	The right saw guide must have a key with a minimal thickness of 1.5 mm to attach the k-wire guide
	Must be intuitive in use
K-wire guide	Must have one hole with 2.1 mm diameter with a tolerance of -0.1 and + 0.4mm[49] to allow entrance of a 1.8mm k-wire into the caudal part
	Must have a keyhole with a width of 1.6 mm and a tolerance of 0.6-0.8 mm[49] to attach to the saw guide
	A unique placement on the right saw guide must be achievable in under 1 minute
Safety	Must have smooth posterior edges to spare the sciatic nerve
	Must have a label to specify the depth of the k-wire to spare the colon
Production and material	Must be producible by additive manufacturing
	Must be sterilizable with an autoclave
	Must be resistant to the wear from inserting the k-wires
	Must be resistant to the wear from supporting the reciprocating saw.

Third, a CT-scan of the synthetic pelvis was obtained using the Brilliance CT Big Bore (Philips Medical Systems Nederland B.V., Best, The Netherlands). The pelvis and sacrum were segmented using Materialise Mimics 24.0. Subsequently, the ADPO with 18^{o} rotation was planned in Materialise 3-matic 16.0, using the custom algorithm that was designed in the in-silico test. The ADPO planning showed a bone contact of 21% for a correction angle of 20 degrees.

Finally, the saw guide and k-wire guide were modelled in Materialise 3-matic 16.0. The first step in the saw guide design was creating a curved beam along the ilium proceeding around the iliac spine. The beam was positioned cranially from the saw path, to determine the position and direction of the saw. The guide was designed to leave the insertion of gluteus maximus, gluteus medius, sartorius, and rectus femoris muscle exposed. The designed beam indicates the sawing direction. It has a height of 8 mm to ensure a stable fit around the ilium and iliac spine and a depth of 20 mm, to support the saw. Subsequently, two 10 mm high fins were designed over the iliac crest tubercle and over the ilium towards the sacroiliac joint to establish a unique placement of the saw guide. Finally, three tubes with an inner diameter of 1.9 mm and outer diameter of 5.0 mm were added to allow passage of the k-wires for fixation of the guide on the ilium. Care was taken to avoid intersection of the k-wires. The length of the tubes was adjusted to ensure support of the k-wire along 50 mm inside the tube and saw guide. The maximum depth of the k-wires was engraved in the tubes to prevent the k-wires from exiting the ilium medially and damaging the iliopsoas muscle and colon. The saw guide does not extend around the sciatic foramen and has no sharp edges or corners posteriorly to prevent damage to the sciatic nerve. The right and left saw guide were labeled to clarify the pelvis side on which they should be positioned and to clarify their orientation on the ilium. The saw guide is shown in Figure 17a.

The k-wire guide was designed only on the right side. The left saw guide was not provided with rotation indicator markings, because the left and right upper pelvic part are connected by the sacrum. Therefore, the left and right upper pelvic parts will rotate at once, thus verification of the rotation indications on one saw guide is sufficient. The k-wire guide was modelled by first creating a block that fits over the right saw guide between the medial and posterior k-wire. The block was thin enough to enable removal of the block while the saw guide remains fixated by k-wires. Subsequently, the saw guide and k-wire guide were connected by a keyed joint. A key of 1.5 mm thickness was added to the saw guide and a keyway of .1.6 mm thickness was created in the k-wire block. This created a unique fit and the ability to slide the k-wire guide onto the saw guide. Next, the k-wire guide was provided with a hole of 2.1 mm diameter to facilitate drilling of the k-wire into the caudal part of the ilium. Finally, three markings were engraved in the right saw guide that indicate a rotation angle of 10, 15, and 20 degrees. The engravings proceeded onto the caudal part of the saw guide, in the same direction as the caudal k-wire. This enabled verification of the rotation angle on the lateral and caudal side of the saw guide. The engravings were narrow to allow smooth passage of the reciprocating saw along the caudal saw guide surface. The k-wire guide is shown in Figure 17b. The guides were printed in-house in nylon using the Fuse 1+ 30W SLS printer (Formlabs, Sommerville, United States).

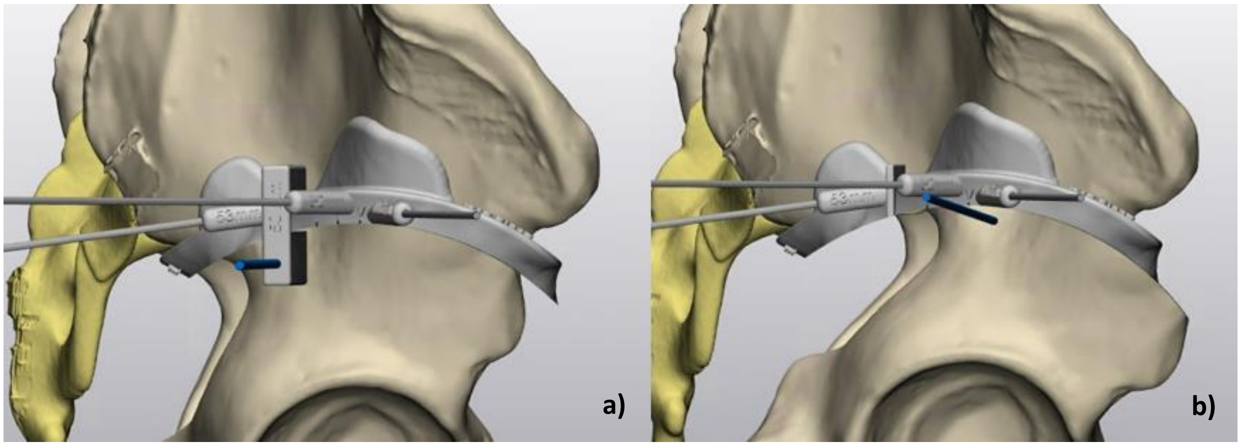


Figure 17. a) The right saw guide and k-wire guide, fixated with k-wires, before rotation, b) the right saw guide and caudal k-wire (blue) after rotation.

3.1.2 Execution of the test

To perform the ADPO on the saw bone, the following materials were used:

- **one saw bone pelvis** (Synbone SND BHD Indahpura, Malaysia)
- **one reciprocating saw** Acculan 3Ti (B. Braun Medical S.E., Oss, The Netherlands)
- **one sawblade** of 50 mm by 1.2 mm by 0.7 mm (Aesculap AG, Tuttlingen, Germany)
- **six k-wires** with a diameter of 1.8 mm
- **one k-wire** with a diameter of 2.0 mm
- **one drill**
- **two bench clamps**
- **two glue clamps**
- **a marker**
- **a ruler**
- **the right and left saw guide**
- **the k-wire guide**

The synthetic bone was placed in bench vices, the right and left saw guides were positioned and fixated with k-wires, as is visible in Figure 18a. The pelvis was cut using the reciprocating saw. Subsequently, the caudal k-wire was placed using the k-wire guide and the pelvis was rotated with 18 degrees. The rotation angle was verified using the caudal k-wire and the rotation marks on the right saw guide. Unfortunately, the pubic bone of the pelvis model was made of foam. The foam allowed significant movement of the right caudal pelvis part relative to the left caudal part. Therefore, the caudal pelvis was returned to its original position as well as possible and the pubic bones were fixated with two 1.8mm k-wires. Finally, the cranial and caudal parts were fixated with one 1.8mm k-wire on each side, placed from the AIIS towards the iliac tubercule, this is visible in Figure 18b. The full protocol for the saw bone test can be found in Appendix C.

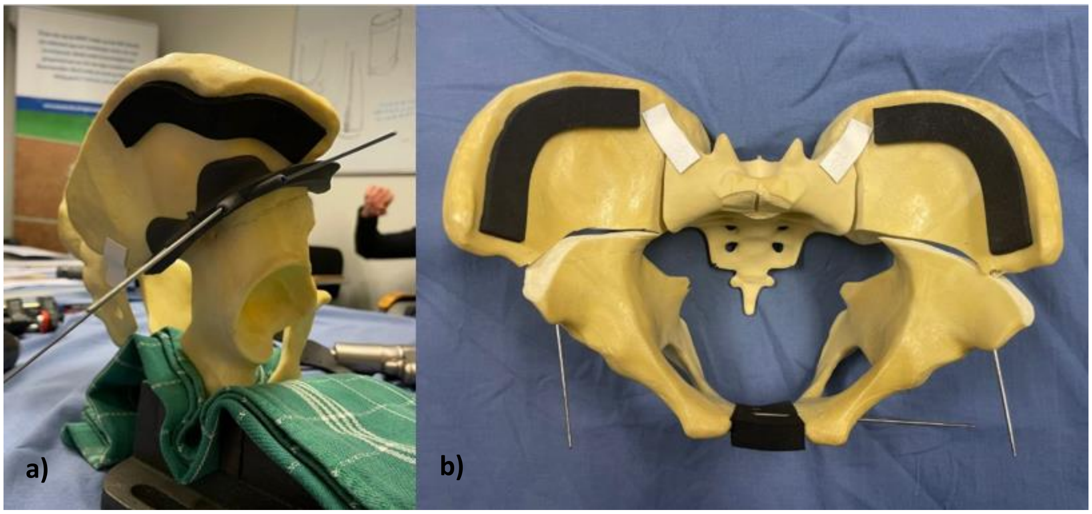


Figure 18. a) Position of the right saw guide on the saw bone and b) the fixation of the saw bone after the ADPO.

3.1.3 Analysis

The saw guide design, k-wire guide design and feasibility of the pelvic osteotomy were evaluated by an orthopedic surgeon who participated in the saw bone test and has more than ten years of experience. The evaluation form can be found in Appendix D. The ADPO operated saw bone was scanned using the Brilliance CT Big Bore. The CT scan was segmented in Materialise Mimics 24.0. The postoperative PSA and bone contact were measured manually in Materialise 3-matic 16.0, using the same method as described in section 2.1. The postoperative PSA was compared to the preoperative PSA to determine the correction angle. The postoperatively achieved PSA and bone contact were compared to preoperative planning and the results of the in-silico test.

3.2 Results

The CT segmentations of the saw bone before and after the ADPO are visualized in Figure 19. The achieved correction angle was 14 degrees, which is a difference of 4 degrees from the planning. The achieved bone contact was 18%, which is a difference of 3% from the planning. A unique fit of the saw guides and k-wire guide was achieved within 10 seconds. The guide did facilitate sawing of the total width of the ilium. The saw was angulated when sawing the ilium, therefore, the surgeon hypothesized the saw guide would not be enough to guide the ADPO in clinical setting. The surgeon further believed that by employing the sawguide in clinical setting, the attachments of the gluteus maximus, gluteus medius, fascia latae, sartorius, and the rectus femoris muscle would not need to be sacrificed and the sciatic nerve would not be jeopardized. The surgeon found the saw guide and k-wire to be intuitive in use. The saw guide and k-wire guide showed to be susceptible to the wear from supporting the reciprocating saw and inserting the k-wires. The requirements met by the saw and k-wire guides are listed in Table 5.

.

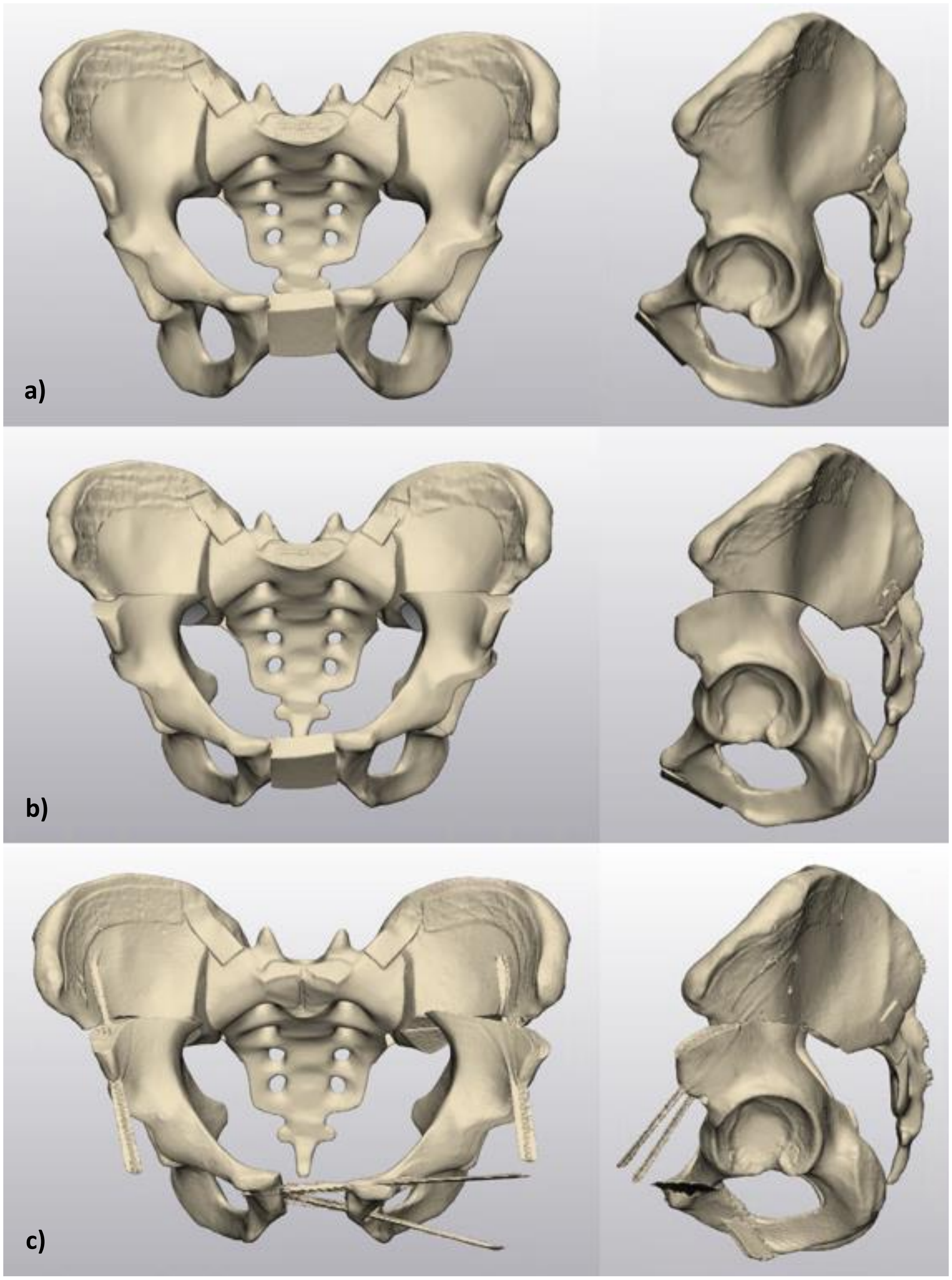


Figure 19. A anterior and lateral view of a) the segmented CT-scan of the saw bone before the ADPO, b) the ADPO planning on the saw bone, and c) the segmented CT-scan of the saw bone after the ADPO.

Table 5. Overview of the saw guide and k-wire guide requirement compliance.

Part	Requirement	Yes/No
Saw guide	A unique placement on the ilium must be achievable in under 1 minute	Yes
	Must guide de saw along the total width of the ilium, measuring 91 mm	Yes
	Must support a 50x1.2x0.7 mm reciprocating saw blade	No
	Must have three holes of 1.9mm diameter with a tolerance of -0.1 and + 0.4mm[49] to allow fixation with 1.8mm k-wires	Yes
	Must leave the gluteus maximus, gluteus medius, tensor fascia latae, sartorius, and rectus femoris muscle attachments uncovered	Yes
	Must have a label to specify the side and orientation of the guide	Yes
	Must have an indicator to verify the rotation angle	Yes
	Must have a key with a minimal thickness of 1.5 mm to attach the k-wire guide	Yes
	Must be intuitive in use	Yes
K-wire guide	Must have one hole with 2.1 mm diameter with a tolerance of -0.1 and + 0.4mm[49] to allow entrance of a 1.8mm k-wire into the caudal part	Yes
	Must have a keyhole with a width of 1.6 mm and a tolerance of 0.6-0.8 mm[49] to attach to the saw guide	Yes
	A unique placement on the right saw guide must be achievable in under 1 minute	Yes
Safety	Must have smooth posterior edges to spare the sciatic nerve	Yes
	Must have a label to specify the depth of the k-wire to spare the colon	Yes
Production and material	Must be producible by additive manufacturing	Yes
	Must be sterilizable with an autoclave	Yes
	Must be resistant to the wear from inserting the k-wires	No
	Must be resistant to the wear from supporting the reciprocating saw.	No

3.3 Discussion

The achieved correction angle of 14 degrees was smaller than the planned 18 degrees. This can be explained by an inaccurate read of the rotation angle indicator. The achieved bone contact of 18% was smaller than the planned bone contact of 21%. This difference can be explained by the imperfect osteotomy, which resulted in a slight difference in rotation and subsequent final position of the pelvic parts and bone contact. Additionally, this bone contact is substantially smaller than the bone contact found in the in-silico study, where the contact surface varied between 24% and 39%. This can be explained by the fact that accidentally, a pelvic model with a displaced symphysis rupture was used. This pelvis has a foam block between the left and right pubis and a displaced left and right pubis. As a result, the pelvis is asymmetric and the angle between the left and right ilia in the axial plane is larger. This causes the bone contact to decrease more when the cranial parts are rotated after the ADPO. The pathologic pelvic model also posed the need for fixation of the pubic bones with k-wires, this should have been done before the ADPO. The fixation of the pubic bones after the ADPO could have resulted in a slight angulation of the right caudal part relative to the left caudal part. This could have deviated the rotation direction from the planning, which could in turn have influenced the correction angle and the bone contact.

The caudal and cranial parts were fixated on the right and left side with a 1.8mm k-wire from each AIIS towards the iliac tubercule. It is visible that the cut planes of the parts do not collide, since no screws were used to pull the pelvic parts together. This could in turn have influenced the obtained rotation angle and bone contact. It is recommended to test the fixation of the cranial and caudal pelvic parts. Pelvis fractures in a line similar to the ADPO path are internally fixated with iliac crest screws[50], an ilium plate[51] or posterior, or anterior column screws[52,53]. External fixation is done with supra acetabular pins or iliac crest pins.[54] When an anterior approach is used, cannulated screw fixation of the ilium using iliac crest screws or supra acetabular screws could be tested. Two screws can be placed on each side of the pelvis; one screw is to be placed from the AIIS towards the iliac tubercle and the other screw must be inserted in the iliac crest towards the posterior point of the caudal ilium part. This way, the cranial and caudal parts are fixated bilaterally at the two bone contact points.

The k-wire guide was an intuitive way to place a k-wire as rotation angle indicator. The tolerance of the k-wire guide, however, was too large. The k-wire guide did not have a tight fit around the saw guide. This can be improved by making the keyway 0.5 mm smaller, resulting in a smaller clearance between the key and the keyway. Additionally, the caudal k-wire in combination with the engraving in the saw guide showed to be an intuitive and effective method to verify the rotation angle. It would be useful to incorporate a similar rotation indication device in the next iteration of the saw guide design.

In clinical practice, this lateral saw guide would not be sufficient to guide the DPO, because the direction and the depth of the saw was not sufficiently restricted and the surgical approach is not possible in clinical setting. Positioning the saw against the saw guide was challenging since the k-wires were in the way of the saw handle. In addition, the 20 mm depth of the saw guide was insufficient to accurately guide the direction of the saw. The k-wire guiding tubes can be repositioned more cranially on the saw guide, farther away from the saw path, to create space for the saw. Another solution could be to crop the k-wires after fixating the saw guide. A third option would be to elongate the depth of the guiding beam from 20 mm to 30 mm. Additionally, the saw depth was not restricted by the guide, this could lead to damage of the iliopsoas muscle or even the colon. Thirdly, the surgeon questioned whether a lateral approach would expose enough ilium to position the saw guide. The lateral approach would require an unacceptably large skin and muscle incision to place the saw guide.

Repeating the saw bone test using an anterior saw guide should be the first step towards clinical implementation of the ADPO**.** An anterior saw guide is recommended to improve the surgical approach, the directional guidance of the saw, and enable restriction of the saw depth. An anterior saw guide should consists of two interconnected guiding blocks. These are to be placed on the medial and lateral side of the ilium and interconnect around the iliac spine. The anterior joint should function as the guiding slot with a depth of at least 30 mm to ensure guidance of the saw direction at the start of the osteotomy. The guides on both sides of the ilium then guide the osteotomy onwards. An oscillating, flexible saw can be used to perform the ADPO. The guide should have a stainless-steel lining or be composed completely of stainless steel. This will prevent the oscillating saw teeth from piercing into the guide. Its anterior entry creates the possibility to predetermine the depth of the saw path and mark this on the saw.

3.4 Conclusion

The correction of the sagittal alignment with the ADPO showed to be practically feasible and effective on a saw bone using a lateral saw guide and rotation indicator. The ADPO could be a suitable alternative for the PSO, to prevent reoperations in the same region or when the PSO is not a safe and effective option. However, the lateral saw guide does not expose enough ilium for saw guide placement, insufficiently guides the ADPO, and does not restrict the saw depth, making the lateral saw guide an invalid option for clinical application. A saw bone study with an anterior guide is required to overcome these problems and further translate the ADPO toward the clinic.

4. Future perspectives

The first recommendation is to practice the procedure frequently to gain an extensive understanding of the required surgical steps, because the ADPO is an intricate procedure. Prior literature states that complications are common, such as nonunion,[22] neurovascular injury[55], especially sciatic nerve injury, bleeding, infection, and femoral acetabular impingement.[23] As was shown in the saw bone study, the osteotomy path is not intuitive. The use of a saw guide is essential for a successful ADPO surgery. Therefore, the surgeon has to fully trust the saw guide and get used to a workflow including this guide. It is strongly recommended to practice the ADPO alongside surgeons with experience in pelvic osteotomies and fractures, namely pediatric orthopedic surgeons and trauma surgeons.

Next to that, a workflow needs to be established to reliably design patient-specific saw guides for every patient undergoing a DPO procedure. Literature shows that such a workflow prevents postponing surgery while waiting for the patient-specific guide design[56]. An automated workflow can contribute to an even larger decrease in labor[57]. A fully automated saw guide planning of the ADPO would result in a considerably shorter 3D planning time and a more reproducible ADPO planning, since the manual labor can be reduced and interobserver variation can be eliminated. This improved efficiency[57] and surgical planning quality is already shown in the orthopedic field, for example in automated femoral osteotomy planning[58]. Our study takes a first step towards an automated workflow, by partially automating the 3D modelling of the DPO.

To automate the whole workflow of a 3D saw guide planning, the segmentation of the pelvis and sacrum, the ADPO modelling, and the saw guide modelling should be automated. The first step would be to automate the segmentation. Lenchik et al. reviewed the automatic segmentation of different organs, including pelvic bone segmentation.[59] They found that first-generation segmentation methods such as thresholding and region growing are often combined with more advanced methods such as atlas-based or statistical models. Employing a combination of these methods can be useful to automate the segmentation in the DPO planning workflow.

The second step would be to fully automate the semi-automated ADPO planning. This can be accomplished by making two adjustments to the script. The first adjustment should be the bony landmark detection for APP definition. Previous research shows the use of the iterative tangential plane (ITP) method[60] or diffeomorphic shape registration[61] to automate bony landmark identification on the pelvis. The ITP method has shown to detect in landmarks with a difference of less than 3 mm from the manual landmark detection, resulting in APP definition with a difference of less than 1 degree from manual landmark detection.[60] This was tested in a population of 100 females and 100 males with an average age of 64 years (SD 13.5 years), which is similar to the age of the patient population with LL. The shape registration showed a difference of a few millimeters between the automatic and manually defined landmarks.[61] These approaches yield promising results and can be added to our algorithm to automate the pelvic bony landmark identification.

The second adjustment should be to automate the osteotomy cylinder diameter definition. We tried to determine the cylinder diameter by using a fraction of the distance from the sacral endplate to the pubis. However, this method did not result in correct intersections of the cylinder and the ilium. Another automation method is recommended; an algorithm that tries different radii to iteratively obtain a radius that best fits the ilium. For this fit, the algorithm should consider the two locations that mark the start and finish of the osteotomy path: 1) the iliac spine between the ASIS and AIIS and 2) the most anterior point of the sciatic foramen. This can be a useful addition to our ADPO planning algorithm to increase planning reproducibility and cut down on planning time. The third step would be to automate the saw guide design, but the saw guide must first be improved and standardized.

After the automation of the ADPO planning and improving the saw guide, a cadaver test is recommended to further test the anatomical feasibility of the ADPO. This cadaver test can be similar to the BEPO test of Ochtman et al.[18], where the BEPO was performed on 10 cadavers with a mean age of 74.3 years. Pre- and postoperatively, CT-scans were obtained to create a surgical planning and compare this with the surgical results. The focus in an ADPO cadaver study should be on two aspects: 1) the feasibility of the ADPO regarding soft tissues and 2) the impact of the ADPO on the gluteus maximus, gluteus medius, tensor fascia latae, sartorius, and recuts femoris muscles and ligaments, sciatic nerve, blood vessels, and sacral position relative to the APP. Finally, a clinical study is required to further examine the safety and the correction of the SVA in patients. Only then can the ADPO be included in the orthopedic toolset for spinal alignment surgery.

References

1. Lafage V, Blondel B, Smith JS, et al. Preoperative planning for pedicle subtraction osteotomy: Does pelvic tilt matter? *Spine Deform*. 2014;2(5):358-366. doi:10.1016/j.jspd.2014.05.006

2. Cheung JPY. The importance of sagittal balance in adult scoliosis surgery. *Ann Transl Med*. 2020;8(2):35-35. doi:10.21037/ATM.2019.10.19

3. Barrey C, Darnis A. Current strategies for the restoration of adequate lordosis during lumbar fusion. *World J Orthop*. 2015;6(1):117-126. doi:10.5312/wjo.v6.i1.117

4. Daniell JR, Osti OL. Failed back surgery syndrome: A review article. *Asian Spine J*. 2018;12(2):372-379. doi:10.4184/asj.2018.12.2.372

5. Ravindra VM, Senglaub SS, Rattani A, et al. Degenerative Lumbar Spine Disease: Estimating Global Incidence and WorldwideVolume. *Glob Spine J*. 2018;8(8):784. doi:10.1177/2192568218770769

6. Thomson S, Jacques L. Demographic characteristics of patients with severe neuropathic pain secondary to failed back surgery syndrome. *Pain Pract*. 2009;9(3):206-215. doi:10.1111/j.1533-2500.2009.00276.x

7. Chang KW, Leng X, Zhao W, et al. Quality control of reconstructed sagittal balance for sagittal imbalance. *Spine (Phila Pa 1976)*. 2011;36(3). doi:10.1097/BRS.0B013E3181EF6828

8. Dreischarf M, Albiol L, Rohlmann A, et al. Age-Related Loss of Lumbar Spinal Lordosis and Mobility – A Study of 323 Asymptomatic Volunteers. *PLoS One*. 2014;9(12). doi:10.1371/JOURNAL.PONE.0116186

9. Kim D, Davis DD, Menger RP. Spine Sagittal Balance. *StatPearls*. August 2021. https://www.ncbi.nlm.nih.gov/books/NBK534858/. Accessed December 20, 2021.

10. Vialle R, Levassor N, Rillardon L, Tempelier A, Skalli W, Guigui P. Radiographic Analysis of the Sagittal Alignment and Balance of the Spine in Asymptomatic Subjects. *J Bone Jt Surgery-American Vol*. 2005;87(2):260-267. doi:10.2106/00004623-200502000-00004

11. Daubs MD, Lenke LG, Cheh G, Stobbs G, Bridwell KH. Adult spinal deformity surgery: Complications and outcomes in patients over age 60. *Spine (Phila Pa 1976)*. 2007;32(20):2238-2244. doi:10.1097/BRS.0B013E31814CF24A

12. Silva FE, Lenke LG. Adult degenerative scoliosis: Evaluation and management. *Neurosurg Focus*. 2010;28(3):1-10. doi:10.3171/2010.1.FOCUS09271

13. Berjano P, Aebi M. Pedicle subtraction osteotomies (PSO) in the lumbar spine for sagittal deformities. *Eur Spine J*. 2014;24(1):49-57. doi:10.1007/s00586-014-3670-7

14. Beech G. Patient Education - Bethesda Chiropractor - Bethesda Back Center - Chiropractors in Bethesda, MD. http://www.bethesdabackcenter.com/articles/dear_doctor_chiro/592995-posture-problems. Published December 20, 2021. Accessed December 20, 2021.

15. Schwab F, Blondel B, Chay E, et al. The Comprehensive Anatomical Spinal Osteotomy Classification. *Neurosurgery*. 2014;74(1):112-120. doi:10.1227/NEU.0000000000000182O

16. How NE, Street JT, Dvorak MF, et al. Pseudarthrosis in adult and pediatric spinal deformity surgery: a systematic review of the literature and meta-analysis of incidence, characteristics, and

risk factors. *Neurosurg Rev*. 2019;42(2):319-336. doi:10.1007/s10143-018-0951-3

17. Youn Y, Smith HC, Pilitsis JG. Failed back surgery syndrome. *Integr Pain Treat into Your Spine Pract*. 2016:19-28. doi:10.1007/978-3-319-27796-7_3

18. Ochtman AEA, Bleys RLAW, Cunningham JE, Öner FC, van Gaalen SM. Correction of the pelvic incidence using a bilateral extending pelvic osteotomy: a proof of concept study. *Arch Orthop Trauma Surg*. 2022;(0123456789). doi:10.1007/s00402-022-04425-1

19. Claessens ML. Patient specific implant design and testing for iliac osteotomy stabilization to restore the sagittal alignment of the spine [Unpublished manuscript]. 2022:1-31.

20. Yener U, Buell TJ, Burke RM, et al. Pedicle Subtraction Osteotomy. *Revis Lumbar Spine Surg*. 2021;10(1):140-151. doi:10.1016/B978-0-323-71201-9.00018-4

21. Pemberton PA. Pericapsular Osteotomy of the Ilium for Treatment of Congenital Subluxation and Dislocation of the Hip. *J Bone Joint Surg Am*. 1965;47(January):65-86. doi:10.2106/00004623-196547010-00004

22. Hamdy RC, Saran N. *Pediatric Pelvic and Proximal Femoral Osteotomies: A Case-Based Approach*.; 2018. doi:10.1007/978-3-319-78033-7

23. Chen C, Wang T-M, Kuo KN. Pelvic Osteotomies for Developmental Dysplasia of the Hip. *Dev Dis Hip - Diagnosis Manag*. April 2017. doi:10.5772/67516

24. Zenz P, Schw W. European Surgical Orthopaedics and Traumatology. *Eur Surg Orthop Traumatol*. 2014:2335-2342. doi:10.1007/978-3-642-34746-7

25. Cheng R, Zhang H, Kernkamp WA, et al. Relations between the Crowe classification and the 3D femoral head displacement in patients with developmental dysplasia of the hip. *BMC Musculoskelet Disord*. 2019;20(1):1-8. doi:10.1186/s12891-019-2838-z

26. Higgins SW, Spratley EM, Boe RA, Hayes CW, Jiranek WA, Wayne JS. A novel approach for determining three-dimensional acetabular orientation: Results from two hundred subjects. *J Bone Jt Surg - Am Vol*. 2014;96(21):1776-1784. doi:10.2106/JBJS.L.01141

27. Babisch JW, Layher F, Amiot LP. The rationale for tilt-adjusted acetabular cup navigation. *J Bone Jt Surg*. 2008;90(2):357-365. doi:10.2106/JBJS.F.00628

28. Abelin-Genevois K. Sagittal balance of the spine. *Orthop Traumatol Surg Res*. 2021;107(1):102769. doi:10.1016/j.otsr.2020.102769

29. Roussouly P, Gollogly S, Berthonnaud E, Dimnet J. Classification of the normal variation in the sagittal alignment of the human lumbar spine and pelvis in the standing position. *Spine (Phila Pa 1976)*. 2005;30(3):346-353. doi:10.1097/01.brs.0000152379.54463.65

30. Bodin A, Roussouly P. Sacral and pelvic osteotomies for correction of spinal deformities. *Eur Spine J*. 2014;24(1):72-82. doi:10.1007/s00586-014-3651-x

31. Makhni MC, Shillingford JN, Laratta JL, Hyun SJ, Kim YJ. Restoration of sagittal balance in spinal deformity surgery. *J Korean Neurosurg Soc*. 2018;61(2):167-179. doi:10.3340/jkns.2017.0404.013

32. Legaye J, Duval-Beaupère G, Hecquet J, Marty C. Pelvic incidence: A fundamental pelvic parameter for three-dimensional regulation of spinal sagittal curves. *Eur Spine J*. 1998;7(2):99-

103. doi:10.1007/s005860050038

33. Le Huec JC, Aunoble S, Philippe L, Nicolas P. Pelvic parameters: origin and significance. *Eur Spine J*. 2011;20 Suppl 5:564-571. doi:10.1007/s00586-011-1940-1

34. Clément JL, Solla F, Amorese V, Oborocianu I, Rosello O, Rampal V. Lumbopelvic parameters can be used to predict thoracic kyphosis in adolescents. *Eur Spine J*. 2020;29(9):2281-2286. doi:10.1007/s00586-020-06373-z

35. Lindstrom, D., Spiegel M. *Shaum's Easy Outline of Statistics*. 2nd ed. McGraw-Hill; 2010.

36. Ochtman AEA, Claessens ML, Oner FC, et al. Pelvic osteotomies for correction of the sagittal alignment of the spine: an in-silico study comparing four different osteotomies. [Unpublished manuscript in preparation of submission].

37. Diebo BG, Shah N V., Boachie-Adjei O, et al. Adult spinal deformity. *Lancet*. 2019;394(10193):160-172. doi:10.1016/S0140-6736(19)31125-0

38. Schlösser TPC, Janssen MMA, Vrtovec T, et al. Evolution of the ischio-iliac lordosis during natural growth and its relation with the pelvic incidence. *Eur Spine J*. 2014;23(7):1433-1441. doi:10.1007/s00586-014-3358-z

39. Trobisch PD, Samdani AF, Pahys JM, Cahill PJ. Analysis of risk factors for loss of lumbar lordosis in patients who had surgical treatment with segmental instrumentation for adolescent idiopathic scoliosis. 2013:1312-1316. doi:10.1007/s00586-013-2756-y

40. Li S, Wang P, Zhang J. Predictors for Postoperative Loss of Lumbar Lordosis After Long Fusions Arthrodesis in Patients with Adult Scoliosis. 2018:531-538. doi:10.12659/MSM.906317

41. Dhand N, Khatar M. Statulator: An online statistical calculator. Sample Size Calculator for Estimating a Single Mean. http://statulator.com/SampleSize/ss1M.html. Accessed March 8, 2023.

42. Broekhuis D, Boyle R, Karunaratne S, Chua A, Stalley P. Custom designed and 3D-printed titanium pelvic implants for acetabular reconstruction after tumour resection. *HIP Int*. 2022. doi:10.1177/11207000221135068

43. Gkagkalis G, Moerenhout K, Rüdiger HA, Müller DA, Letovanec I, Cherix S. Pelvic Chondrosarcoma Treated by En Bloc Resection with Patient-Specific Osteotomy Guides and Reimplantation of the Extracorporeally Irradiated Bone as an Osseocartilaginous Structural Orthotopic Autograft: A Report of Two Cases with Description of the Su. *Case Rep Orthop*. 2021;2021:1-9. doi:10.1155/2021/5512143

44. Han Q, Zhang K, Zhang Y, et al. Individual resection and reconstruction of pelvic tumor with three-dimensional printed customized hemi-pelvic prosthesis: A case report. *Med (United States)*. 2019;98(36). doi:10.1097/MD.0000000000016658

45. Park JW, Kang HG, Kim JH, Kim HS. The application of 3D-printing technology in pelvic bone tumor surgery. *J Orthop Sci*. 2021;26(2):276-283. doi:10.1016/j.jos.2020.03.004

46. Ma S, Xiao L, Guo D, Shi Q, Shen R, Li X. Application of 3D-printed osteotomy guides in periacetabular osteotomy: A short-term clinical study. *Int J Artif Organs*. 2022;45(11):945-951. doi:10.1177/03913988221120026

47. Wang X, Liu S, Peng J, et al. Development of a novel customized cutting and rotating template for

Bernese periacetabular osteotomy. *J Orthop Surg Res*. 2019;14(1):1-10. doi:10.1186/s13018-019-1267-x

48. Gómez-Palomo JM, Estades-Rubio FJ, Meschian-Coretti S, Montañez-Heredia E, De Santos-De La Fuente FJ. Internal Hemipelvectomy and Reconstruction Assisted by 3D Printing Technology Using Premade Intraoperative Cutting and Placement Guides in a Patient with Pelvic Sarcoma: A Case Report. *JBJS Case Connect*. 2019;9(4):1-7. doi:10.2106/JBJS.CC.19.00060

49. Oceanz. Design Guidelines For PA11, TPU and ALUMIDE parts produced with Selective Laser Sintering. 2022:1-2.

50. AO Surgery Reference. ORIF - Iliac crest. https://surgeryreference.aofoundation.org/orthopedic-trauma/adult-trauma/pelvic-ring/stable-ring/orif-iliac-crest?searchurl=%2Fsearchresults. Accessed February 17, 2023.

51. AO surgery reference. ORIF through sequential approaches. ORIF through sequential approaches. Accessed February 17, 2023.

52. AO Surgery Reference. Posterior column screw fixation. https://surgeryreference.aofoundation.org/orthopedic-trauma/periprosthetic-fractures/hip/spontaneous-acetabular-fracture/posterior-column-screw-fixation?searchurl=%2Fsearchresults. Accessed February 17, 2023.

53. AO Surgery Reference. Anterior column screw fixation. https://surgeryreference.aofoundation.org/orthopedic-trauma/periprosthetic-fractures/hip/spontaneous-acetabular-fracture/anterior-column-screw-fixation?searchurl=%2Fsearchresults. Accessed February 17, 2023.

54. AO Surgery Reference. External fixation. https://surgeryreference.aofoundation.org/orthopedic-trauma/adult-trauma/pelvic-ring/acute-pelvic-treatment/external-fixation?searchurl=%2Fsearchresults. Accessed February 17, 2023.

55. Clohisy JC, Barrett SE, Gordon JE, Delgado ED, Schoenecker PL. Periacetabular osteotomy in the treatment of severe acetabular dysplasia. Surgical technique. *J Bone Joint Surg Am*. 2006;88 Suppl 1:65-83. doi:10.2106/00004623-200603001-00007

56. Williams FC, Hammer DA, Wentland TR, Kim RY. Immediate Teeth in Fibulas: Planning and Digital Workflow With Point-of-Care 3D Printing. *J Oral Maxillofac Surg*. 2020;78(8):1320-1327. doi:10.1016/j.joms.2020.04.006

57. Kurmis AP, Ianunzio JR. Artificial intelligence in orthopedic surgery: evolution, current state and future directions. *Arthroplasty*. 2022;4(1). doi:10.1186/s42836-022-00112-z

58. de Galiza Barbosa F, Galgano SJ, Botwin AL, et al. Genitourinary imaging. *Clin PET/MRI*. 2022:540-549. doi:10.1016/B978-0-323-88537-9.00012-X

59. Lenchik L, Heacock L, Weaver AA, et al. Automated Segmentation of Tissues Using CT and MRI: A Systematic Review. *Acad Radiol*. 2019;26(12):1695-1706. doi:10.1016/j.acra.2019.07.006

60. Fischer MCM, Krooß F, Habor J, Radermacher K. A robust method for automatic identification of landmarks on surface models of the pelvis. *Sci Rep*. 2019;9(1):1-10. doi:10.1038/s41598-019-49573-4

61. Kuchař M, Henyš P, Rejtar P, Hájek P. Shape morphing technique can accurately predict pelvic

bone landmarks. *Int J Legal Med*. 2021;135(4):1617-1626. doi:10.1007/s00414-021-02501-6

62. Hartvigsen J, Hancock MJ, Kongsted A, et al. What low back pain is and why we need to pay attention. *Lancet*. 2018;391(10137):2356-2367. doi:10.1016/S0140-6736(18)30480-X

63. Schwab F, Patel A, Ungar B, Farcy J-P, Lafage V. *Adult Spinal Deformity-Postoperative Standing Imbalance How Much Can You Tolerate? An Overview of Key Parameters in Assessing Alignment and Planning Corrective Surgery*. Vol 35.

64. Rothenfluh DA, Mueller DA, Rothenfluh E, Min K. Pelvic incidence-lumbar lordosis mismatch predisposes to adjacent segment disease after lumbar spinal fusion. *Eur Spine J*. 2015;24(6):1251-1258. doi:10.1007/s00586-014-3454-0

65. Rubery PT, Lander ST, Mesfin A, Sanders JO, Thirukumaran CP. Mismatch between Pelvic Incidence and Lumbar Lordosis is the Key Sagittal Plane Determinant of Patient Outcome at Minimum 40 Years after Instrumented Fusion for Adolescent Idiopathic Scoliosis. *Spine (Phila Pa 1976)*. 2022;47(5):E169-E176. doi:10.1097/BRS.0000000000004277

66. Boulay C, Tardieu C, Hecquet J, et al. Sagittal alignment of spine and pelvis regulated by pelvic incidence: Standard values and prediction of lordosis. *Eur Spine J*. 2006;15(4):415-422. doi:10.1007/s00586-005-0984-5

67. Schwab FJ, Blondel B, Bess S, et al. Radiographical spinopelvic parameters and disability in the setting of adult spinal deformity: A prospective multicenter analysis. *Spine (Phila Pa 1976)*. 2013;38(13). doi:10.1097/BRS.0b013e318292b7b9

68. Ochtman AEA, Kruyt MC, Jacobs WCH, et al. Surgical Restoration of Sagittal Alignment of the Spine: Correlation with Improved Patient-Reported Outcomes: A Systematic Review and Meta-Analysis. *JBJS Rev*. 2020;8(8):e1900100. doi:10.2106/JBJS.RVW.19.00100

69. Lau D, Haddad AF, Deviren V, Ames CP. Complication profile associated with S1 pedicle subtraction osteotomy compared with 3-column osteotomies at other thoracolumbar levels for adult spinal deformity: Series of 405 patients with 9 S1 osteotomies. *J Neurosurg Spine*. 2020;33(5):577-587. doi:10.3171/2020.4.SPINE20239

70. Yang C, Zheng Z, Liu H, Wang J, Kim YJ, Cho S. Posterior vertebral column resection in spinal deformity: a systematic review. *Eur Spine J*. 2016;25(8):2368-2375. doi:10.1007/s00586-015-3767-7

71. Ochtman AEA, Bleys RLAW, Cunningham JE, Öner FC, van Gaalen SM. Correction of the pelvic incidence using a bilateral extending pelvic osteotomy: a proof of concept study. *Arch Orthop Trauma Surg*. 2022. doi:10.1007/s00402-022-04425-1

72. Pape D, Dueck K, Haag M, Lorbach O, Seil R, Madry H. Wedge volume and osteotomy surface depend on surgical technique for high tibial osteotomy. *Knee Surgery, Sport Traumatol Arthrosc*. 2013;21(1):127-133. doi:10.1007/s00167-012-1913-x

73. Nejima S, Kumagai K, Fujimaki H, et al. Increased contact area of flange and decreased wedge volume of osteotomy site by open wedge distal tibial tuberosity arc osteotomy compared to the conventional technique. *Knee Surg Sports Traumatol Arthrosc*. 2021;29(10):3450-3457. doi:10.1007/S00167-020-06296-8

74. Meriç Ünal A, Budeyri A, Baykal B. Comparison of contact surface areas of metatarsal diaphyseal

osteotomies for correction of hallux valgus: Experimental study. *Acta Orthop Traumatol Turc*. 2020;54(4):430-437. doi:10.5152/J.AOTT.2020.17481

75. van Heerwaarden R, Najfeld M, Brinkman M, Seil R, Madry H, Pape D. Wedge volume and osteotomy surface depend on surgical technique for distal femoral osteotomy. *Knee Surg Sports Traumatol Arthrosc*. 2013;21(1):206-212. doi:10.1007/S00167-012-2127-Y

76. Cosson M, Boukerrou M, Lacaze S, et al. A study of pelvic ligament strength. *Eur J Obstet Gynecol Reprod Biol*. 2003;109(1):80-87. doi:10.1016/S0301-2115(02)00487-6

77. De Decker A, Fergusson R, Ondruschka B, Hammer N, Zwirner J. Anatomical structures at risk using different approaches for sacrospinous ligament fixation. *Clin Anat*. 2020;33(4):522-529. doi:10.1002/ca.23404

78. Böhme J, Lingslebe U, Steinke H, et al. The extent of ligament injury and its influence on pelvic stability following type II anteroposterior compression pelvic injuries--A computer study to gain insight into open book trauma. *J Orthop Res*. 2014;32(7):873-879. doi:10.1002/JOR.22618

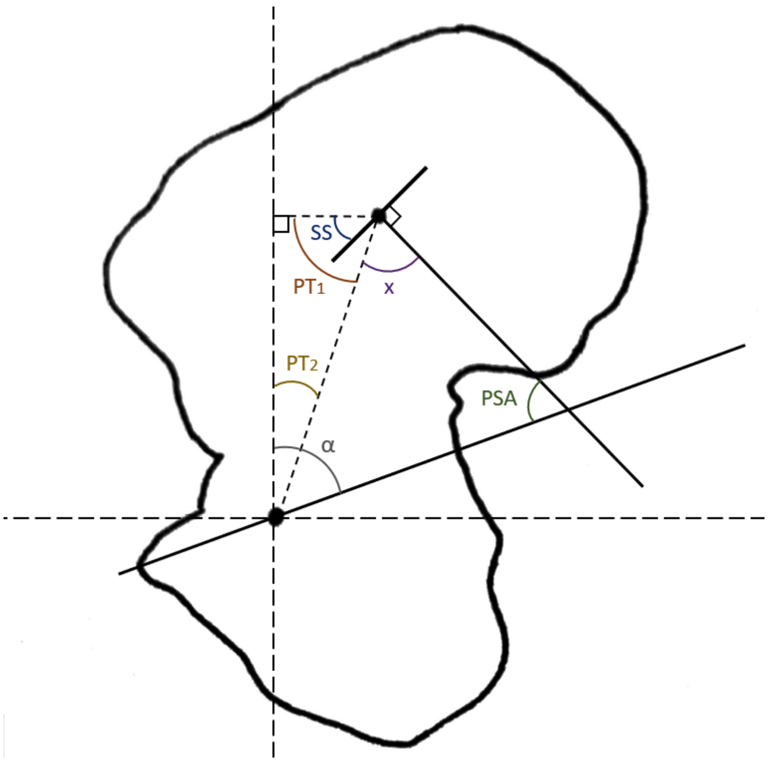
79. Abdelfattah A, Moed BR. Ligamentous contributions to pelvic stability in a rotationally unstable open-book injury: A cadaver study. *Injury*. 2014;45(10):1599-1603. doi:10.1016/j.injury.2014.05.026

80. Fox DB, Tomlinson JL, Cook JL, Breshears LM. Principles of uniapical and biapical radial deformity correction using dome osteotomies and the center of rotation of angulation methodology in dogs. *Vet Surg*. 2006;35(1):67-77. doi:10.1111/J.1532-950X.2005.00114.X

81. Nikolaou C, Black C, Ochoa JJ, Fitzpatrick N. Guidelines for the Execution of True Spherical Osteotomies Using a Modified Dome Blade Design. *Vet Comp Orthop Traumatol*. 2020;33(2):71-81. doi:10.1055/s-0039-3399526

Appendix A: Pubic sacral angle (PSA) formulas

i. PSA is related to the SS



$PSA = 180 - x - (\alpha - PT2)$

$x = 90 - (PT1 - SS)$

$PT1 = 180 - 90 - PT2$

$x = 90 - (180 - 90 - PT2 - SS)$

$x = 90 - (90 - PT2 - SS)$

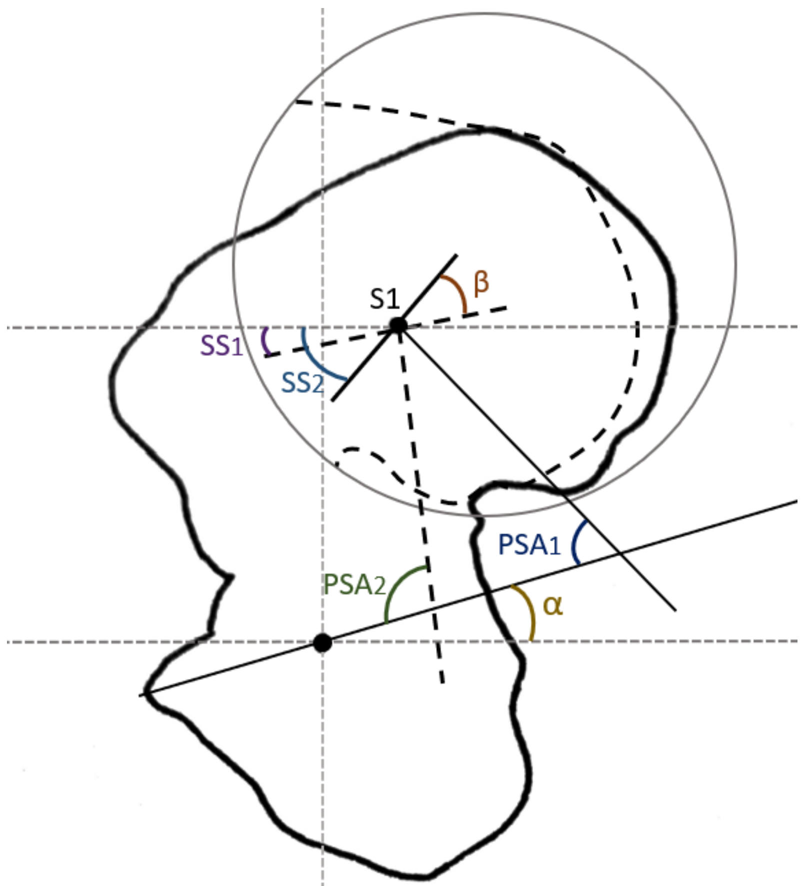
$x = PT2 + SS$

$PSA = 180 - PT2 - SS - (\alpha - PT2)$

$PSA = 180 - x - PT2 - SS - \alpha + PT2$

$\boldsymbol{PSA = 180 - SS - \alpha}$

ii. The PSA changes when the cranial part is rotated compared to the caudal part



$PSA1 = 180 - SS1 - \alpha$

$PSA2 = 180 - SS2 - \ \alpha$

$PSA2 = 180 - (SS1 - \beta) - \alpha = 180 - SS1 + \beta$

$\Delta PSA = PSA2 - PSA1$

$PSA \ = (180 - SS1 + \beta) - \ (180 - SS1 - \alpha) - \alpha$

$\boldsymbol{\Delta PSA = \beta}$

Appendix B: Overview literature review saw guides

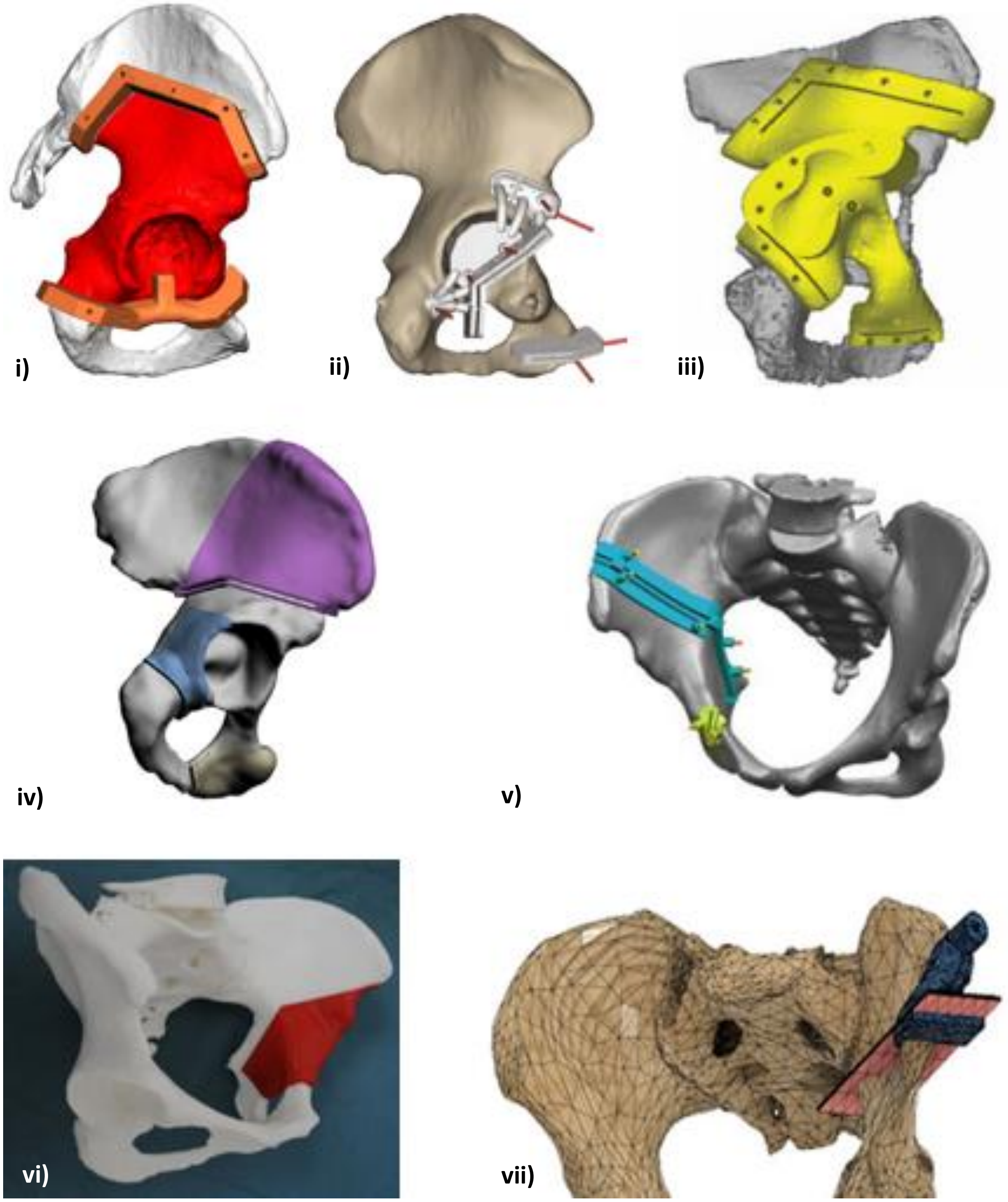


Figure 20. i) Lateral ilium saw guide[42], lateral acetabulum saw guide[43], lateral ilium saw guide[44], lateral ilium saw guide[45], medial peri-acetabular saw guide[46], medial Bernese osteotomy saw guide[47], amterior ilium saw guide[48].

Appendix C: Saw bone test protocol

1. Secure the synthetic bone pelvis with bench vices and clamps.
2. Position the right saw guide. This is depicted in Figure 21i.
3. Mark the k-wire depth depicted on the right saw guide, on the k-wires.
4. Secure the right saw guide with k-wires. This is illustrated in Figure 21ii.
5. Position the left saw guide.
6. Mark the k-wire depth depicted on the left saw guide, on the k-wires.
7. Secure the left saw guide with k-wires.
8. Saw the right ilium with a reciprocating saw, starting posteriorly, below the right saw guide.
9. Place the k-wire guide for the caudal k-wire.
10. Mark the depth that is depicted on the k-wire guide on the k-wire.
11. Position the caudal k-wire guide and secure the caudal k-wire. This is shown in Figure 21iii.
12. Remove the k-wire guide. This is depicted in Figure 21iv.
13. Saw the left ilium with a reciprocating saw, starting posteriorly, below the left saw.
14. Rotate the upper pelvic part 20 degrees until the caudal k-wire aligns with the arrow on the right saw guide. This is depicted in Figure 21v.
15. Secure the right ilium by drilling a k-wire from the AIIS towards the tubercule of the iliac crest.
16. Secure the left ilium by drilling a k-wire from the AIIS towards the tubercule of the iliac crest.

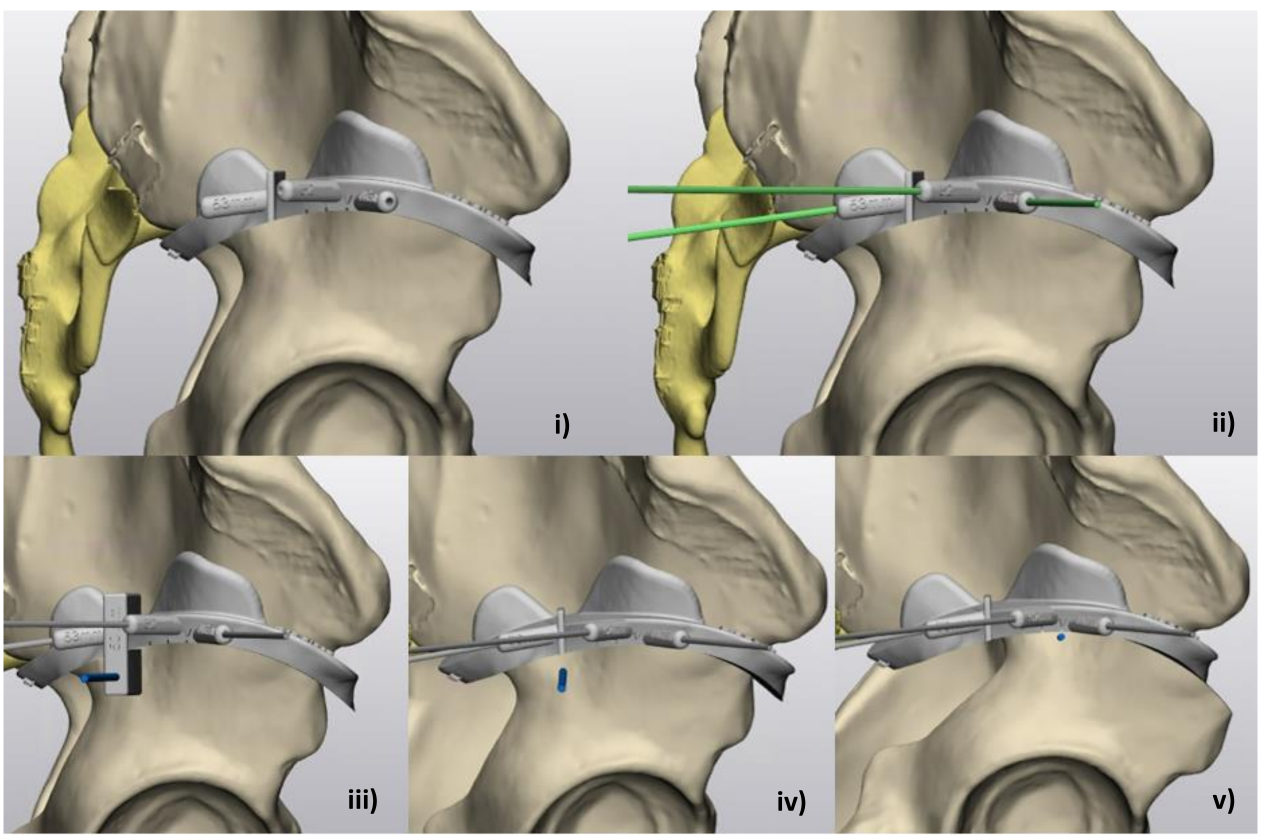


Figure 21. i) position of het right saw guide, ii) right saw guide securing, iii) caudal k-wire positioning, iv) k-wire guide removal, and v) rotation cranial pelvic part.

Appendix D: Evaluation form saw bone test

Op een schaal van 1 tot 5, hoe makkelijk waren de volgende onderdelen te plaatsen
en hoe schat je de haalbaarheid van de DPO met behulp van deze zaagmal in?
Hier is 1 heel moeilijk en 5 heel makkelijk.

	1 (Heel moeilijk)	2	3	4	5 (Heel makkelijk)
1. Zaagmal:					
a. Positioneren zaagmal	☐	☐	☐	☐	☒
b. Bepalen diepte k-draden	☐	☐	☐	☐	☒
c. Fixeren zaagmal met k-draden	☐	☐	☐	☐	☒
d. Introduceren zaag tegen zaagmal	☐	☒	☐	☐	☐
e. Afsteunen zaag tijdens zagen	☐	☐	☒	☐	☐
f. Bepalen zaagdiepte	☐	☐	☒	☐	☐
g. Hoe intuïtief was de zaagmal in gebruik?	☐	☐	☐	☒	☐
2. Caudale k-draad mal:					
a. Positioneren k-draad mal	☐	☐	☐	☐	☒
b. Bepalen diepte k-draad	☐	☐	☐	☐	☒
c. Plaatsen caudale k-draad	☐	☐	☐	☐	☒
d. Hoe intuïtief was de k-draad mal in gebruik?	☐	☐	☐	☐	☒
3. Roteren iliumdelen:					
a. Rotatierichting bepalen	☐	☐	☐	☐	☒
b. Hoe intuïtief was het aflezen van de rotatiehoek op zaagmal?	☐	☐	☐	☐	☒

Toelichting mits van toepassing:

Introduceren zaagmal lastig doordat k-draden in de weg zaten.

Hieronder volgen een aantal statements met betrekking tot de haalbaarheid van de DPO in de klinische praktijk. Geef aan of je het hier helemaal mee oneens, oneens, neutraal, eens of helemaal mee eens bent.

In klinische praktijk

	Helemaal oneens	Oneens	Neutraal	Eens	Helemaal eens
4. Bij een laterale benadering zou het ilium in praktijk voldoende kunnen worden vrijgelegd om de zaagmal te plaatsen	☐	☐	☒	☐	☐
5. Door het plaatsen van de zaagmal hoeven de aanhechtingen van de m. gluteus maximus, m. gluteus medius, m. tensor fascia latae, m. sartorius en de m. rectus femoris niet te worden opgeofferd.	☐	☐	☐	☒	☐
6. Door het gebruik van deze zaagmal wordt de nervus ischiadicum in gevaar gebracht	☐	☒	☐	☐	☐
7. Deze zaagmal zou in de praktijk voldoende zijn om de DPO te geleiden	☐	☒	☐	☐	☐
8. Het botcontact na rotatie is voldoende voor een stabiele fixatie	☐	☒	☐	☐	☐
9. Na de rotatie heeft het sacrum een positie die klinisch haalbaar is	☐	☐	☒	☐	☐
10. De caudale k-draad guide i.c.m. de rotatie indicator op de zaagmal zou in de praktijk voldoende zijn om de rotatiehoek te bepalen	☐	☐	☐	☒	☐

Verbeterpunten:

Als contact% > 25% dan geen probleem

Rugligging met anterieure benadering beter.

Flexibel zaagblad i.c.m. stainless steel zaagmal

Appendix E: Pelvic osteotomies for correction of the sagittal alignment of the spine: an in-silico study comparing four different osteotomies.

A.E.A. Ochtman, MD[1*], M.L. Claessens, BA[1*], F.C. Öner, MD, PhD[1], M.C. Kruyt, MD, PhD[1]

1. Department of Orthopedics, University Medical Center Utrecht, the Netherlands
2. Department of developmental bioengineering Twente University, the Netherlands
*Both authors contributed equally to the manuscript

Introduction The aim of this study was to compare the correction of the pelvic sacral angle (PSA) of the bilateral extended pelvic osteotomy (BEPO) and three types of dome pelvis osteotomy (DPO) in patients with loss of lumbar lordosis (LL). **Methods** These four osteotomies were performed on 10 human pelves in an in-silico study using Materialise 3-matic 3D modelling software. **Results** The cranial pelvic part was rotated with 20 degrees, resulting in a PSA correction of 20 degrees and a respective mean bone contact of 34% (SD 9%), 28% (SD 10%), and 31% (SD 5%) for the SEDPO, SIDPO, and ADPO. **Conclusion** The ADPO proved to be technically feasible and effective. A cadaveric study and clinical study are required to determine the anatomical viability and safety in humans. The DPO is regarded as a useful tool in the orthopedic arsenal for spinal alignment surgery based on in-silico and practical tests.

Keywords Loss of lumbar lordosis/adult spinal deformity • sagittal alignment of the spine • bilateral extended pelvic osteotomy • dome pelvic osteotomy • 3D modelling

Introduction

The human evolution to a bipedal posture has led to morphological changes in both the spine and the pelvis.[32,38] The position of the sacrum within the pelvis has an immense influence on the global spinal equilibrium since its relation to the femoral heads regulates lumbar lordosis (LL). This relation is determined by the pelvic incidence (PI), a parameter defined as the angle between the line perpendicular to the sacral plate at its midpoint, and the line connecting this point to the axis of the femoral heads (Figure 1).[32] Sagittal imbalance is often the result of decreased lumbar lordosis that can be a consequence of lumbar degenerative disc disease, a major global problem that increased the years lived with disability by more than 50% since 1990[62]. Over a decade ago, Schwab et al. already stated that a mismatch between the PI and LL can lead to a standing imbalance, when LL < PI±9.[63] Since then, PI-LL mismatch has been increasingly recognized as a key element in spinal sagittal alignment.[64–66] The compensation mechanisms to keep the trunk above the hips such as retroversion of the pelvis by increasing pelvic tilt (PT) are tiring and therefore associated with reduced quality of life.[67,68]

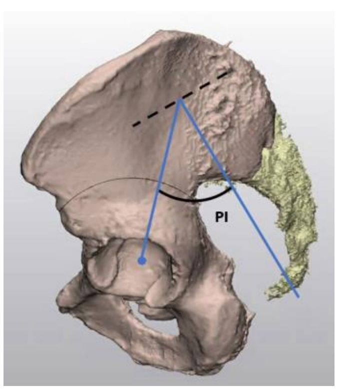


Fig 1. Pelvic incidence (PI): the angle between the line perpendicular to the sacral plate at its midpoint, and the line connecting the point to the axis of the femoral heads.

Correction of severe sagittal malalignment requires extensive correction osteotomies of the lumbar spine, such as pedicle subtraction osteotomies and vertebral column resections. However, these procedures are associated with a complication risk up to 27.4%, including neurological deficit and material failure.[69,70] Especially if previous osteotomies have failed, revision is even more demanding. As an alternative, a bilateral pelvic open-wedge osteotomy between the sacral plate and the femoral heads was proposed by several authors.[30,71] Some case series and laboratory work confirmed the feasibility of this approach, but this procedure has a significant risk of a fracture in the posterior hinge with subsequent pelvic instability and less correction of PI than expected. To circumvent this problem dome shape osteotomies may be a solution. These osteotomies are well known for limb alignment and have the advantage of very predictable and controllable rotation with maintenance of bone-to-bone contact. To explore the potential of such an osteotomy in relation to the open wedge we study the most optimal location, its potential for substantial correction and anatomical limitations in an in-silico model study.

Materials and Methods

Three dome shaped pelvic osteotomies were developed and compared to the BEPO regarding correction angle and bone contact surface. The correction angle is the most important parameter, since the goal of the treatment is to correct the sagittal alignment of the spine. The bone contact surface determines the possible fixation and stability of the cranial and caudal pelvic part.

Data preparation

Ten computed tomography angiography (CTA) scans were selected from an existing clinical database (5 males and 5 females, mean age 27 years old (range 21-35)). All CTA scans included the whole pelvis and were performed with a slice thickness of 0.9 mm. None of the subjects had any history of pelvic or hip fractures or surgery. The anonymized data were acquired retrospectively and was judged not to be subject to the Medical Research Involving Human Subjects Act (WMO) by the Medical Ethical Committee, as described in IRB Protocol Number 16-612/C. The pelvises were segmented using Mimics 24.0 (Materialise, Leuven, Belgium).

Three-dimensional (3D) bone model generation

A robust pelvic coordinate was defined using the bony landmarks on the pelvis; the anterior pelvic plane (APP) coordinate system. The coronal plane, or anterior pelvic plane, of the coordinate system is defined by the right anterior superior iliac spine (R-ASIS), left anterior superior iliac spine (L-ASIS) and the midpoint of the pubic tubercles (MPT).[26,25] The center point of the APP coordinate system is defined in the middle of the right and left ASIS. The sagittal plane is defined by a plane perpendicular to the APP and through the midpoint of the R-ASIS and L-ASIS and the MPT. The axial plane is defined perpendicular to the APP and the sagittal plane through the center of the coordinate system. The APP, sagittal and axial plane together create the APP coordinate system.

Subsequently, four pelvic osteotomies were performed on all ten pelvises with 3-Matic: a bilateral extending pelvic osteotomy and three dome pelvic osteotomies. We considered 1) the natural rotation axis of the spine with respect to the pelvis and 2) the feasibility of the surgical approach and procedure to determine the DPO locations. The first DPO is performed around center of the sacral endplate (SEDPO), since this is the location where the PSA is measured. The second DPO is performed around the sacroiliac joint (SIDPO), since this is the location where the spine theoretically rotates with respect to the pelvis. The third DPO is performed around the acetabulum centers (ADPO), as the acetabulum provides the functional rotation of upper body with respect to the lower body by pelvic tilt. This is also known as an accessible location to perform a pelvic osteotomy, since multiple periacetabular osteotomies, such as the Pemberton[22,23] and the Chiari osteotomy[24] are performed here. (Figure 2).

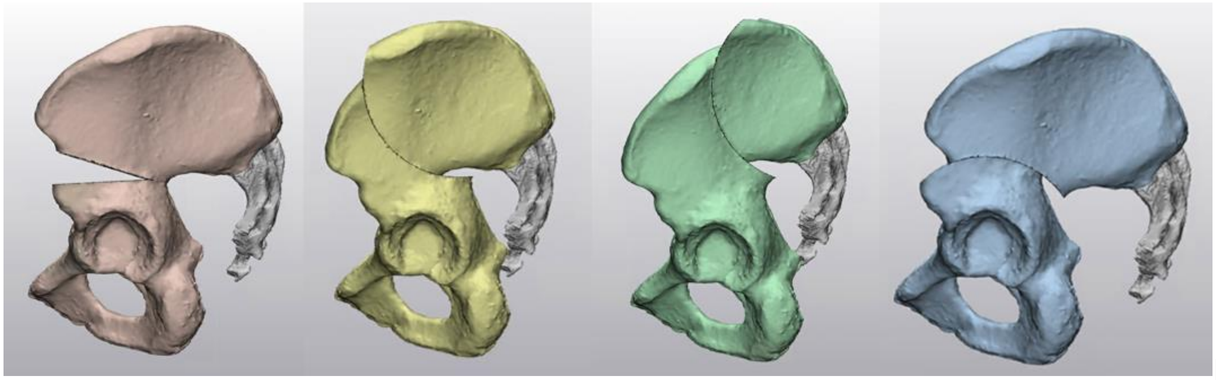


Fig 2. a) bilateral extending pelvic osteotomy (BEPO), b) dome pelvic osteotomy around the sacral endplate (SEDPO), c) dome pelvic osteotomy around the sacroiliac joint (SIDPO) and d) periacetabular dome pelvic osteotomy (ADPO).

The execution of the osteotomies was automated using Pycharm 2022.2.3 (JetBrains, Prague, Czech Republic). To model the BEPO, the osteotomy plane was defined perpendicular to the APP and through a point between the ASIS and AIIS and the most ventral point of the greater sciatic foramen. Next, the cranial part was rotated 20 degrees around an axis parallel to the x-axis of the APP one centimeter proximal to the posterior point of the osteotomy. To perform the DPOs, the center of the sacral endplate, the center of the sacroiliac joint, and the midpoint of the two acetabula centers were defined. Then a cylinder was created. The axis of the cylinder was defined as a line parallel to the x-axis of the APP, located in each of these three points. The diameter of this cylinder is dependent on the type of osteotomy that is performed and the size of the pelvis. The diameters were adjusted until the cylinder intersected the iliac crest anteriorly and the great sciatic notch posteriorly for the SEDPO and SISPO. For the ADPO, the diameter of the cylinder was adjusted until it intersects the pelvis between the ASIS and AIIS anteriorly and the great sciatic notch posteriorly. In all osteotomies, a cylinder diameter is chosen that does not intersect the roof part of the acetabulum and does not intersect the musculus sartorius attachment. The ilium is rotated relative to the ischium with 10, 15 and 20 degrees.

Outcome measures

To compare the different pelvic osteotomies, two primary outcome measures were obtained: bone contact surface between the cranial and caudal pelvis part and the effect on sagittal alignment of the spine. The quantify the bone contact, the cut surface and the bone contact surface of the ilium parts were measured after 10, 15 and 20 degrees. From this, the contact surface relative to the osteotomy surface were calculated using a predefined formula[14]:

$$\text{Bone contact surface percentage } (\%) = \frac{\text{bone contact surface of ilium parts } (\text{mm}^2)}{\text{bone surface at osteotomy surface } (\text{mm}^2)}$$

To quantify the effect on sagittal spinal alignment a new parameter was used: the pubic sacral angle (PSA), defined as the angle between the left pubic tubercule, the left acetabulum center and a line perpendicular to the center of the sacral endplate in the sagittal plane (Figure 3). The PSA can be used to measure the correction angle measured in the sagittal plane of the APP for every step of the rotation of the ilium, resulting in three angle measurements.

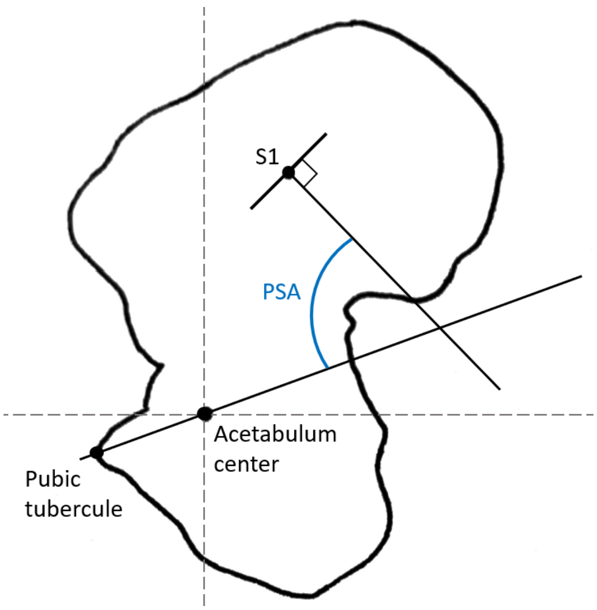


Fig 3. Pubic sacral angle (PSA): the angle between the pubic tubercule, the center of the acetabulum and the center of the sacral endplate.

Statistical analysis

Statistical analyses were performed with Statistical Package for the Social Sciences software (SPSS 23.0, SPSS Inc., Chicago, IL, USA). The bone contact surface was shown to be normally distributed using the Shapiro-Wilk test. Therefore, the statistical analysis of the rotation angle and the PSA was performed using the Pearson correlation. Statistical significance was set at $p<0.05$.

Results

Bone contact surface

The percentage bone contact surface after SEDPO, SIDPO and ADOP are shown in Table 1 and visualized in Figure 4. The variation in bone contact surface for different correction angles is shown in Figure 5. The SIDPO shows the largest mean bone contact percentage. However, ADPO shows the smallest variation of bone contact percentage between the different pelvises for each angle. For the BEPO, no bone contact surface could be measured.

Correction of PSA

The correction of the PSA for different correction angles are shown in Figure 6. For each of the ten pelvises and each of the DPO's, the rotation angle and the PSA correction are identical.

Least squares method (LSM)

For each of the ten pelvises, all the rotation angles and DPO locations, the LSM line through the bone contact surface percentages per rotation angle had a coefficient of determination larger than 0.75. The average LSM fit per rotation angle and DPO location is visualized in yellow in Figure 5. It shows the LSM line fitted on the SEDPO has the flattest slope and the LSM line fitted on the ADPO has the steepest slope.

Table 1. The percentage bone contact surface after 20 degrees of rotation of the SEDPO, SIDPO, and ADOP

Pelvis #	SEDPO	SIDPO	ADPO
1	38.83	26.11	31.96
2	26.38	28.09	39.18
3	38.91	35.57	32.04
4	31.53	8.93	25.12
5	49.40	47.40	37.04
6	27.60	25.75	32.77
7	22.46	25.97	25.84
8	43.01	38.28	28.53
9	40.95	27.55	29.27
10	22.43	18.41	24.20
Average	34.15	28.21	30.59
Standard deviation	8.87	10.04	4.73

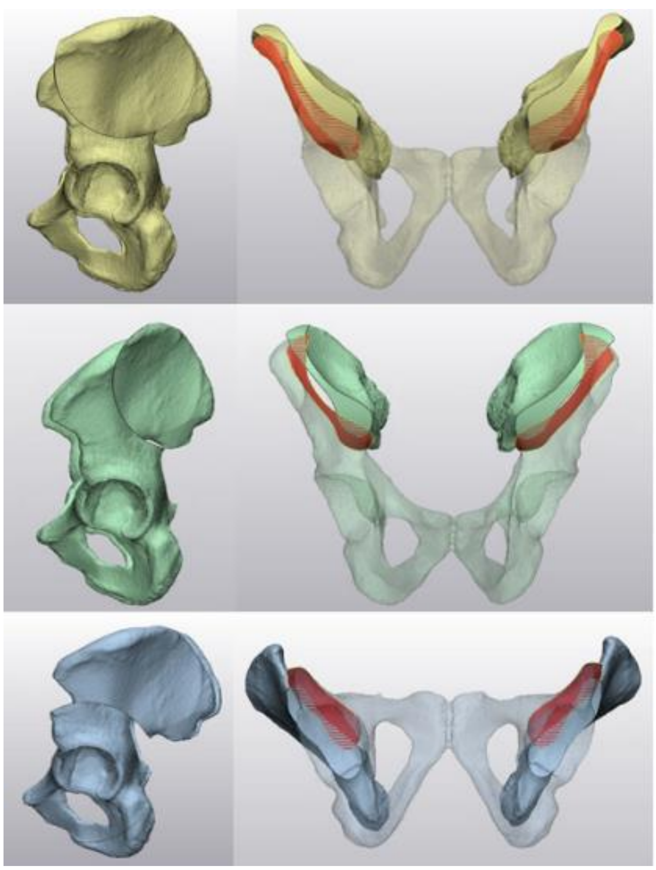


Fig 4. From left to right; Lateral and caudal view of the dome osteotomy around the sacral endplate, sacroiliac joint and acetabular dome osteotomy after ilium rotation of 20 degrees. The bone contact between the ilium parts is visualized in striped red.

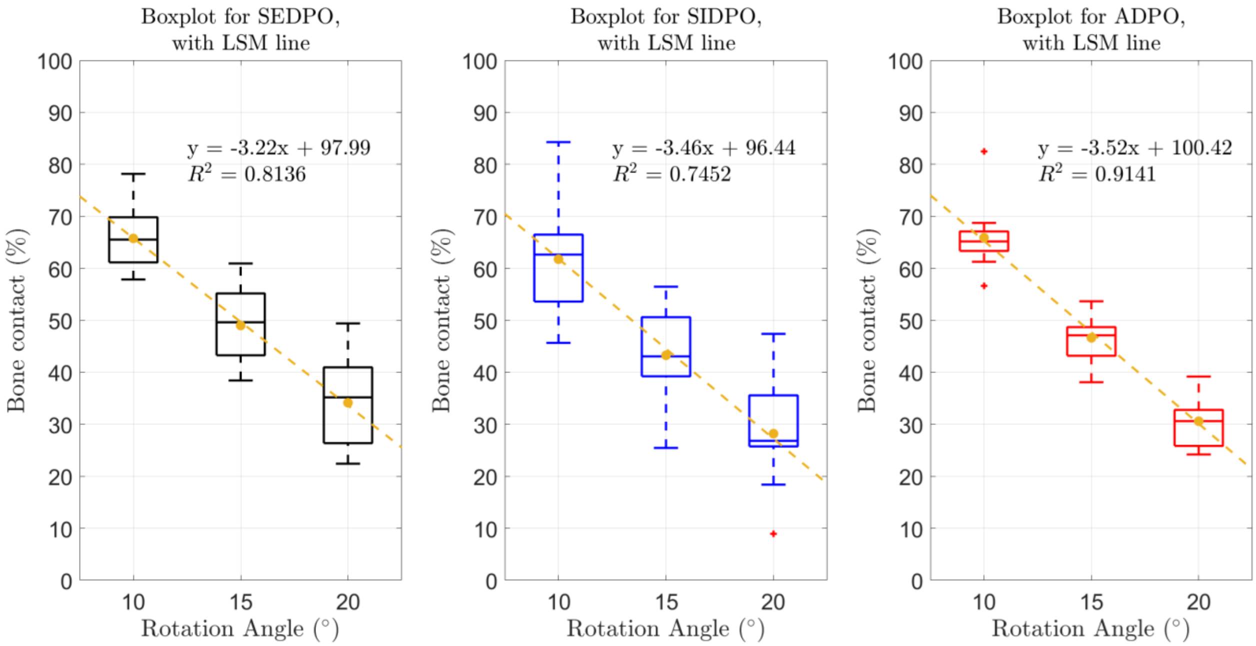


Fig *Figure 5. Boxplot of the bone contact surface percentage for correction angles 10, 15 and 20 degrees after the SEDPO (black), SIDPO (blue) and ADPO (red) with a least squares fitted line through all data points (yellow).*

Discussion

In the present study we compared four different pelvic osteotomies to correct spinopelvic parameters in a 3D model. Our data suggest that the ADPO is the most reliable and feasible pelvic osteotomy to correct PSA and therefore sagittal spinal malalignment. For the first primary aim, bone contact surface, ADPO showed the most reliable results (31%, SD 5%). Although the SEDPO showed the highest bone contact surface, the results were less reliable due to the wide range, which is less appealing in the clinical setting. Obviously, for the BEPO no bone contact surface could be measured. When performing this osteotomy in a clinical setting, a specifically designed cage should be inserted to support bone consolidation. Bone contact surface has been an object of interest for studies about correctional tibial osteotomies and hallux valgus correction osteotomies.[72–75] Although, to our best knowledge, a minimal percentage of bone contact to create the optimal healing environment is not available in the current literature. Our second primary aim was to quantify the effect of the pelvic dome osteotomy on the sagittal alignment of the spine. Therefore, we proposed the new parameter PSA. The most apparent eligible parameter to quantify the effect was PI. However, to quantify the change in sagittal alignment after a pelvic dome osteotomy, the rotation of the cranial pelvic part must be quantified, and PI did not meet that requirement (Figure 7). This is also shown by Roussouli et al., where a Chiari osteotomy which is comparable to the ADPO, did not show a change in PI.[30] A parameter that is suitable for the three proposed DPOs should have one line that is defined cranial to the sacral, sacroiliac joint or acetabular osteotomy line and a second line that is caudal to the osteotomy line, such as PSA. Even more, PSA is independent of the position of the patient,[62] changes when the rotation angle of the ilium changes,22 and the landmarks could be identified robustly. Lastly, the PSA is correlated with the sacral slope following the formula: PSA = 180 – SS – α, where α is the angle of the lower line of the PSA angle and the vertical line.[34] Therefore, PSA could be used as a parameter to quantify the effect on sagittal alignment. For all four pelvic osteotomies, the mean correction of PSA was exact the angle of the osteotomy, so this was not a differentiating factor.

Our secondary outcome measurement was anatomic feasibility, including surgical approach, risk of ischiatic nerve impingement and loss of strength of the sacropelvic ligaments. Various gynecologic researchers have studied the sacrotuberous (ST) and sacrospinous (SS) ligaments in order to prevent or treat pelvic organ prolapse. Cosson et al.

performed a cadaveric test to compare maximal strength of different pelvic ligaments. They found the prevertebral and iliopectineal ligaments significantly stronger that the ST and SS ligaments,[76] which suggest this osteotomy would not have much impact on potential pelvic organ prolapse. On the other hand, studies about pelvic traumatic injuries proved these ligaments to play an important role in stability of the pelvis.[77–79] The influence of an ADPO on the ST and SS ligaments remains uncertain and should be further researched. Under normal circumstances, only elderly patients would be eligible for this procedure, so there is no risk for women in their fertile age to experience problems with future pregnancies.

The place of the osteotomy is the same for the ADPO and the BEPO, between the sacral plate and the femoral heads, where the evolution of the lordotic angulation between the ischium and the ilium led to a more energy-efficient upright position in bipedal position.[2] The main advantage of a dome osteotomy over an open-wedge osteotomy is the combined ability to correct the alignment while maintaining bone apposition.[80,81] Another important advantage, specifically for a pelvic osteotomy, is a more guided saw cute to the anterior side of the ischiatic foramen and therefore, no risk of a unforeseen fracture. In our open-wedge technique, the posterior hinge could provide stability to the correction. Even more, due to this posterior hinge the risk of injury to the ischiatic nerve or impingement is relatively low compared to the dome osteotomy. However, such an unforeseen fracture could seriously undermine the stability leading to additional fixation needs in the clinical setting, especially because it is a bilateral procedure.

In conclusion, the ADPO is the most reliable and feasible pelvic osteotomy that was tested in this in-silico study regarding correction of PSA and bone surface contact. Therefore, this osteotomy could be an eligible alternative procedure to correct spinal sagittal malalignment. However, anatomic feasibility should be further investigated in cadaveric studies and the effect on global spinal alignment and safety should be researched in a prospective clinical trial.

References

1. Legaye J, Duval-Beaupère G, Hecquet J, et al. *Pelvic Incidence: A Fundamental Pelvic Parameter for Three-Dimensional Regulation of Spinal Sagittal Curves*. Vol 7.; 1998.

2. Schlösser TPC, Janssen MMA, Vrtovec T, et al. Evolution of the ischio-iliac lordosis during natural growth and its relation with the pelvic incidence. *European Spine Journal*. 2014;23(7):1433-1441. doi:10.1007/s00586-014-3358-z

3. Hartvigsen J, Hancock MJ, Kongsted A, et al. What low back pain is and why we need to pay attention. *The Lancet*. 2018;391(10137):2356-2367. doi:10.1016/S0140-6736(18)30480-X

4. Schwab F, Patel A, Ungar B, Farcy JP, Lafage V. *Adult Spinal Deformity-Postoperative Standing Imbalance How Much Can You Tolerate? An Overview of Key Parameters in Assessing Alignment and Planning Corrective Surgery*. Vol 35.

5. Rothenfluh DA, Mueller DA, Rothenfluh E, Min K. Pelvic incidence-lumbar lordosis mismatch predisposes to adjacent segment disease after lumbar spinal fusion. *European Spine Journal*. 2015;24(6):1251-1258. doi:10.1007/s00586-014-3454-0

6. Rubery PT, Lander ST, Mesfin A, Sanders JO, Thirukumaran CP. Mismatch between Pelvic Incidence and Lumbar Lordosis is the Key Sagittal Plane Determinant of Patient Outcome at Minimum 40 Years after Instrumented Fusion for Adolescent Idiopathic Scoliosis. *Spine (Phila Pa 1976)*. 2022;47(5):E169-E176. doi:10.1097/BRS.0000000000004277

7. Boulay C, Tardieu C, Hecquet J, et al. Sagittal alignment of spine and pelvis regulated by pelvic incidence: Standard values and prediction of lordosis. *European Spine Journal*. 2006;15(4):415-422. doi:10.1007/s00586-005-0984-5

8. Schwab FJ, Blondel B, Bess S, et al. Radiographical spinopelvic parameters and disability in the setting of adult spinal deformity: A prospective multicenter analysis. *Spine (Phila Pa 1976)*. 2013;38(13). doi:10.1097/BRS.0b013e318292b7b9

9. Ochtman AEA, Kruyt MC, Jacobs WCH, et al. Surgical Restoration of Sagittal Alignment of the Spine: Correlation with Improved Patient-Reported Outcomes: A Systematic Review and Meta-Analysis. *JBJS Rev*. 2020;8(8):e1900100. doi:10.2106/JBJS.RVW.19.00100

10. Lau D, Haddad AF, Deviren V, Ames CP. Complication profile associated with S1 pedicle subtraction osteotomy compared with 3-column osteotomies at other thoracolumbar levels for adult spinal deformity: Series of 405 patients with 9 S1 osteotomies. *J Neurosurg Spine*. 2020;33(5):577-587. doi:10.3171/2020.4.SPINE20239

11. Yang C, Zheng Z, Liu H, Wang J, Kim YJ, Cho S. Posterior vertebral column resection in spinal deformity: a systematic review. *European Spine Journal*. 2016;25(8):2368-2375. doi:10.1007/s00586-015-3767-7

12. Bodin A, Roussouly P. Sacral and pelvic osteotomies for correction of spinal deformities. *Eur Spine J*. 2015;24 Suppl 1(1):72-82. doi:10.1007/S00586-014-3651-X

13. Ochtman AEA, Bleys RLAW, Cunningham JE, Öner FC, van Gaalen SM. Correction of the pelvic incidence using a bilateral extending pelvic osteotomy: a proof of concept study. *Arch Orthop Trauma Surg*. Published online 2022. doi:10.1007/s00402-022-04425-1

14. Cheng R, Zhang H, Kernkamp WA, et al. Relations between the Crowe classification and the 3D femoral head displacement in patients with developmental dysplasia of the hip. *BMC Musculoskelet Disord*. 2019;20(1). doi:10.1186/S12891-019-2838-Z

15. Pape D, Dueck K, Haag M, Lorbach O, Seil R, Madry H. Wedge volume and osteotomy surface depend on surgical technique for high tibial osteotomy. *Knee Surgery, Sports Traumatology, Arthroscopy*. 2013;21(1):127-133. doi:10.1007/s00167-012-1913-x

16. Nejima S, Kumagai K, Fujimaki H, et al. Increased contact area of flange and decreased wedge volume of osteotomy site by open wedge distal tibial tuberosity arc osteotomy compared to the conventional technique. *Knee Surg Sports Traumatol Arthrosc*. 2021;29(10):3450-3457. doi:10.1007/S00167-020-06296-8

17. Meriç Ünal A, Budeyri A, Baykal B. Comparison of contact surface areas of metatarsal diaphyseal osteotomies for correction of hallux valgus: Experimental study. *Acta Orthop Traumatol Turc*. 2020;54(4):430-437. doi:10.5152/J.AOTT.2020.17481

18. Nejima S, Kumagai K, Fujimaki H, et al. Increased contact area of flange and decreased wedge volume of osteotomy site by open wedge distal tibial tuberosity arc osteotomy compared to the conventional technique. *Knee Surg Sports Traumatol Arthrosc*. 2021;29(10):3450-3457. doi:10.1007/S00167-020-06296-8

19. van Heerwaarden R, Najfeld M, Brinkman M, Seil R, Madry H, Pape D. Wedge volume and osteotomy surface depend on surgical technique for distal femoral osteotomy. *Knee Surg Sports Traumatol Arthrosc*. 2013;21(1):206-212. doi:10.1007/S00167-012-2127-Y

20. Bodin A, Roussouly P. Sacral and pelvic osteotomies for correction of spinal deformities. *European Spine Journal*. 2014;24(1):72-82. doi:10.1007/s00586-014-3651-x

21. Legaye J, Duval-Beaupère G, Hecquet J, Marty C. Pelvic incidence: A fundamental pelvic parameter for three-dimensional regulation of spinal sagittal curves. *European Spine Journal*. 1998;7(2):99-103. doi:10.1007/s005860050038

22. Roussouly P, Gollogly S, Berthonnaud E, Dimnet J. Classification of the normal variation in the sagittal alignment of the human lumbar spine and pelvis in the standing position. *Spine (Phila Pa 1976)*. 2005;30(3):346-353. doi:10.1097/01.BRS.0000152379.54463.65

23. Clément JL, Solla F, Amorese V, Oborocianu I, Rosello O, Rampal V. Lumbopelvic parameters can be used to predict thoracic kyphosis in adolescents. *Eur Spine J*. 2020;29(9):2281-2286. doi:10.1007/S00586-020-06373-Z

24. Cosson M, Boukerrou M, Lacaze S, et al. A study of pelvic ligament strength. *European Journal of Obstetrics and Gynecology and Reproductive Biology*. 2003;109(1):80-87. doi:10.1016/S0301-2115(02)00487-6

25. De Decker A, Fergusson R, Ondruschka B, Hammer N, Zwirner J. Anatomical structures at risk using different approaches for sacrospinous ligament fixation. *Clinical Anatomy*. 2020;33(4):522-529. doi:10.1002/ca.23404

26. Böhme J, Lingslebe U, Steinke H, et al. The extent of ligament injury and its influence on pelvic stability following type II anteroposterior compression pelvic injuries - A computer study to gain insight into open book trauma. *Journal of Orthopaedic Research*. 2014;32(7):873-879. doi:10.1002/jor.22618

27. Abdelfattah A, Moed BR. Ligamentous contributions to pelvic stability in a rotationally unstable open-book injury: A cadaver study. *Injury*. 2014;45(10):1599-1603. doi:10.1016/j.injury.2014.05.026

28. Fox DB, Tomlinson JL, Cook JL, Breshears LM. Principles of uniapical and biapical radial deformity correction using dome osteotomies and the center of rotation of angulation methodology in dogs. *Vet Surg*. 2006;35(1):67-77. doi:10.1111/J.1532-950X.2005.00114.X

29. Nikolaou C, Black C, Ochoa JJ, Fitzpatrick N. Guidelines for the Execution of True Spherical Osteotomies Using a Modified Dome Blade Design. *Veterinary and Comparative Orthopaedics and Traumatology*. 2020;33(2):71-81. doi:10.1055/s-0039-

Appendix F: Sacrum saw guide

Naast de activiteiten die ik hierboven heb beschreven, heb ik vanaf november gemiddeld een dag per week besteed aan het maken van een klinische zaagmal voor een scoliosepatiënt. Zo'n zaagmal was nooit eerder gebruikt in het UMC Utrecht. Het proces van het maken van de zaagmal begon bij het segmenteren van alle cervicale, thoracale en lumbale wervels, het pelvis en het sacrum. Aan de hand hiervan kon worden beoordeeld dat het sacrum links een hemiwervel had en dat er sprake was van scoliose, vermoedelijk als gevolg van deze hemiwervel. Daarnaast kon worden beoordeeld dat deze patiënt niet 5, maar 6 lumbale wervels had, en dat de lumbale lordose erg groot was. Samen met Moyo Kruijt heb ik geïnventariseerd wat zijn hulpvraag aan het 3Dlab was voor deze patiënt. Hij wilde een zaagmal hebben waarmee een osteotomie van het sacrum kon worden uitgevoerd om de hemiwervel te verwijderen zodat de laterale richting van de rug kon worden gecorrigeerd. Daarnaast wil hij een anatomisch model van de zesde lumbale wervel (L6), het sacrum inclusief de operatieve stappen en het linker ilium.

De eisen aan de zaagmal waren als volgt:

- De zaagmal moet de een sacrumosteotomie geleiden zodat de hemiwervel verwijderd kan worden.
- De zaagmal moet groot genoeg zijn om een oscillerende zaag voldoende ondersteunen om een unieke zaagrichting te geleiden
- De zaagmal moet een unieke correcte plaatsing hebben
- De zaagmal moet bruikbaar zijn voor een posterieure chirurgische benadering van het sacrum
- De zaagmal moet een handvat hebben om het vanuit posterieur in te brengen
- De zaagmal moet de cauda equina niet in gevaar brengen
- De zaagmal moet de L6 zenuwwortel niet in gevaar brengen

De chirurgische stappen in de laterale correctie voor deze patiënt waren als volgt:

1. Laminectomie van L6
2. Laminectomie, facetectomie en processus transversus verwijderen van de linker hemiwervel van het sacrum
3. Verwijderen van het hemiwervellichaam van het sacrum zodat alleen het bot ter plekke van de sacro-iliacale gewricht en het stuk boven de osteotomielocatie nog staat
4. Subtractieosteotomie van het sacrum met de zaagmal
5. Correctie van L6

De losse botdelen als gevolg van de laminectomieën en de subtractie osteotomie zijn in het anatomisch model verbonden door een balkjes die kunnen worden geschoven in een sleuf. De correctie van L6 is opgenomen in het model als een boogje, welke kan buigen. Door deze toevoegingen kan op het model de 'correctie' van L6 worden uitgevoerd. In Figure 22 is het anatomische model van L6, het sacrum en linker ilium te zien. De chirurgische stappen zijn weergegeven in Figure 23.

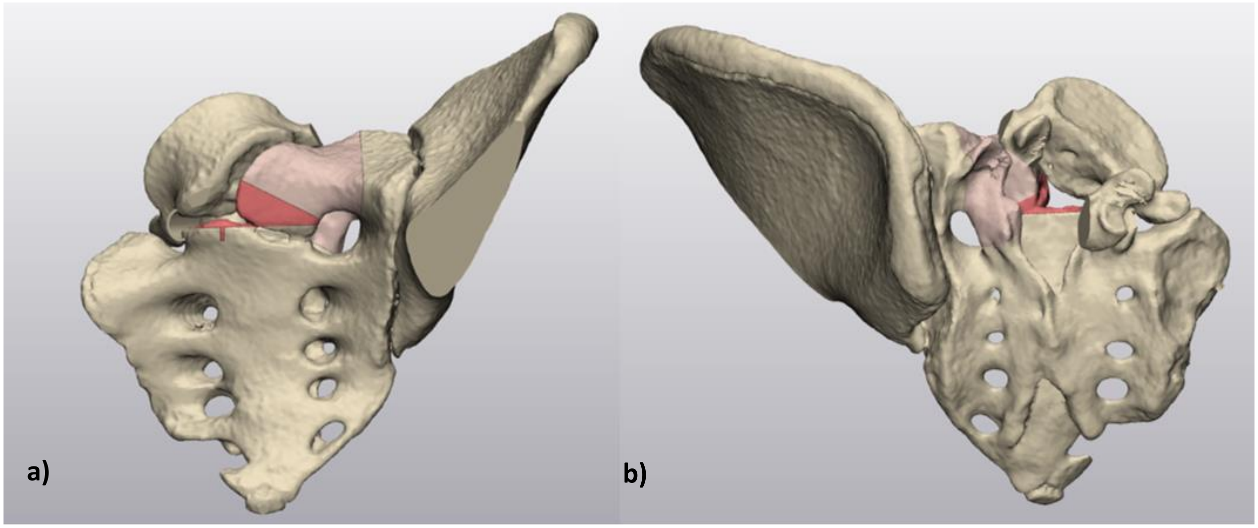


Figure 22. Anatomisch model met een a) anterieure view en b) posterieure view van het sacrum met voorbereiding voor subtractie in roze, subtractieosteotomie van de sacrale dekplaat in rood, L6 en een deel van het linker ilium.

Tijdens het designproces heb ik steeds afwisselend overlegd met Moyo en Joëll Magré van het 3Dlab om nieuwe iteraties van mijn ontwerp te beoordelen en verbeterpunten op te stellen. Deze iteraties en de notulen van de overlegmomenten heb ik gedocumenteerd in een gedeeld bestand, zodat het designproces kan worden teruggelezen. Als afsluiting van het designproces is de zaagmal gecontrolleerd en in een overleg met Joëll en Moyo goedgekeurd. Het anatomisch model en de zaagmal zijn geprint in nylon door middel van selective laser sitering (SLS) bij Oceanz (Oceanz 3D printing, Ede, Nederland). Deze zullen in het UMC Utrecht worden gesteriliseerd zodat deze tijdens de operatie kunnen worden gebruikt. In Figure 24 is de uiteindelijke zaagmal te zien.

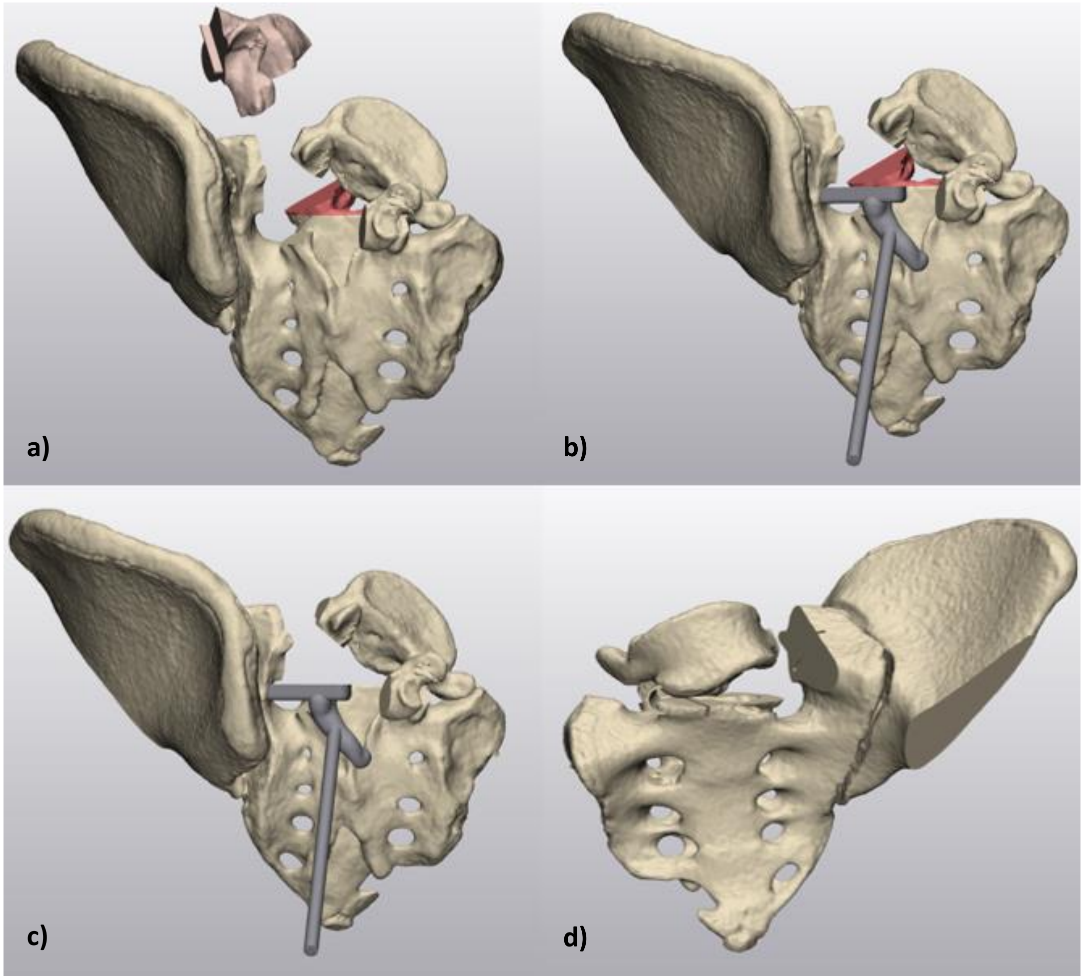


Figure 23. Chirurgische stappen: a) laminectomie sacrum en voorbereiding subtractieosteotomie van sacrale dekplaat, b) plaatsen zaagmal, c) subtractie osteotomie lans de zaagmal en d) correctie van L6.

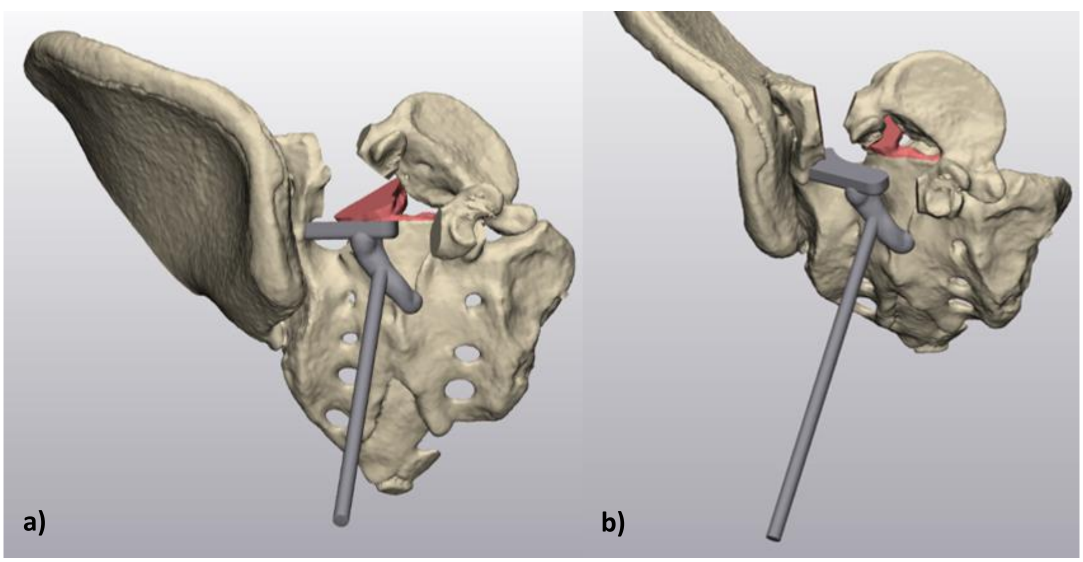


Figure 24. a) posterior view en b) cranial view van de zaagmal met handvat, mediaal een sleeve waarmee de mal steunt op de rand van het sacral canal en lateraal een support foot.