The challenge of sagittal spinal alignment

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General introduction and thesis outline

GENERAL INTRODUCTION

Good alignment of the human spine is an equilibrium in which the body maintains an efficient, balanced and energy-saving posture in a bipedal position. This could be accomplished when the body's center of gravity is within the base of support, a concept known as the *cone of economy* described by Dubousset in the early 1970s.[1] Later, he named the realization of upright standing the *chain of balance*.[2] All neuro-musculoskeletal components of the body work together to maintain a standing position with a horizontal gaze, but according to Dubousset, the key components of this chain are the feet, pelvis and cranium. Walking upright with the center of body mass above the pelvis places more stress on the lumbar spine, hips, knees and feet, leading to types of arthrosis that are only seen in humans. Furthermore, vertebral fractures, neuromuscular disorders and surgical interventions can also lead to abnormal curvatures of the spine. This group of conditions is called adult spinal deformity (ASD). With the aging of the population and an increasing life expectancy,[3,4] this is becoming an ever bigger issue.

Anatomy of the spine

The spinal column consists of 33 vertebrae, providing support and flexibility to the human body and protecting the spinal cord. In general, there are seven cervical, twelve thoracic, five lumbar and five fused sacral vertebrae. A physiological human spine is straight in the coronal plane and has an S-shape in the sagittal plane, by Hippocrates (460-370 BCE) described as *ithiscolios*.[5] In the sagittal plane, the spine exhibits four curvatures: cervical lordosis (CL), thoracic kyphosis (TK), lumbar lordosis (LL) and sacral kyphosis (SK). As the pelvis could be considered as a single 'pelvic vertebra',[1] a fifth curvature could be added: lordotic angulation between the ischium and ilium (pelvic lordosis [PL]).[6] The load distribution on the spine depends more on its shape and curvature in the sagittal plane than in the coronal plane.[7] Non-human primates show almost no curvatures in their thoracolumbar spine or pelvis.[8] This means that an extreme LL should be maintained in an upright position to keep the upper body straight above the pelvis. The alternative 'bent-hip, bent-knee' posture, as seen by chimpanzees, leads to tremendous forces of the ischiofemoral muscles. Both of these mechanisms are only sustainable for occasional bipedal locomotion.[9] PL was a prerequisite to keep the upper body straight above the pelvis in the human evolution from quadrupedalism to bipedalism.[10]

Pathology of the spine

The evolution to bipedalism gave humans the enormous advantage that the hands could be used for non-locomotive tasks,[11,12] but also introduced challenges. Lordotic ilio-ischial angulation led to the narrowing of the bony birth canal, requiring evolutionary compromises like earlier births.[13] It also introduced unique biomechanical forces on the spine.[14] Humans developed spinal pathologies such as

Scheuermann's disease and idiopathic scoliosis due to the increase of dorsal shear forces and the permanent axis of gravity anterior to the spine.[15] In the adult spine, these increased forces may also cause degenerative changes leading to degenerative scoliosis, spondylolisthesis or lumbar stenosis with neurological symptoms, mostly unique to humans. Although some individuals will stay asymptomatic,[16] it leads to chronic back pain and/or disability for others.[17] The development of degenerative disc disease (DDD) of the lumbar spine is multifactorial, including genetics, lifestyle and injury. The aging lumbar spine undergoes several structural and functional changes.[18] Facet joint arthrosis, osteophyte formation, endplate sclerosis and neural foramina stenosis often lead to degenerative scoliosis and/or spondylolisthesis.[19] The increased dorsal shear forces on the human spine led to the adaptation of the lumbar spine with thicker intervertebral discs to bear the higher load as a result of the vertical orientation of the spine.[20,21] These stresses on the lower back may lead to loss of height of the intervertebral discs, resulting in a decrease in LL and an increase in TK with a forward-leaning posture that shifts the center of gravity even more ventral.[22] These postural changes exacerbate progressive degenerative changes even more due to compensatory mechanisms such as hypokyphosis of the thoracic spine, hyperlordosis of the lumbar spine, extension of the pelvis, flexion in the knees and ankle extension.[23] This vicious circle is needed for active and passive compensatory mechanisms to maintain an upright posture until it fails.

Analysis of sagittal spinal alignment

Analysis of global sagittal spinal alignment requires parameters that measure the orientation of the whole spine and combine both spinal and pelvic alignment. In the current literature, many spinal parameters have been described. The angles of the consecutive kyphotic and lordotic curves of the cervical (C2-C7), thoracic (Th1-Th12) and lumbar (L1-L5) spine are measured to identify regional angulations. The most used spinal parameter to analyze global alignment is the sagittal vertical axis (SVA), which is used interchangeably with the C7 plumb line (C7pl) and is defined as the horizontal distance between a vertical line drawn from the center of the C7 vertebral body and the posterior-superior corner of S1 (Figure 1A, **Chapter 2**).[24] Correct measurement requires a calibrated image as this is a distance measurement. Therefore, angular parameters have been proposed such as T1 pelvic angle (TPA),[25] spinopelvic angle (SPA)[26] and spinosacral angle (SSA)[27] (Figure 1).

Furthermore, three crucial pelvic parameters have been described: pelvic incidence (PI), sacral slope (SS) and pelvic tilt (PT). PI is defined as the angle between the line perpendicular to the endplate of S1 and the line connecting the center of the superior endplate of S1 to the midpoint between the femoral heads.[28] This parameter remains relatively constant for each individual after growth with a slight tendency to increase with age and on CT imaging compared to X-rays[29] and to vary depending on the pelvic version during X-ray, suggesting a potential functional motion at the sacroiliac joints[30]. SS and PT are related even more to pelvis orientation and vary with the body position.

SS is defined as the angle between the line connecting the center of the superior endplate of S1 to the midpoint between the femoral heads and a horizontal line and PT as the angle between the same line connecting S1 and the femoral heads and a vertical line (Figure 1H-J, **Chapter 2**).[28] These parameters are mathematically linked by the formula: PI = SS + PT.[31]

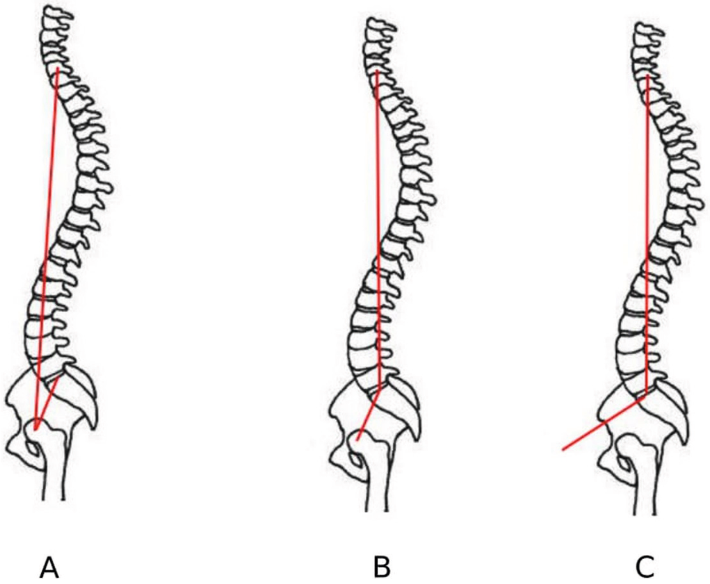

Figure 1.
1-A T1 pelvic angle (TPA): the angle between the line connecting the midpoint of the vertebral body of Th1 to the midpoint between the femoral heads and the line connecting the center of the superior endplate of S1 to the midpoint between the femoral heads.
1-B Spinopelvic angle (SPA): the angle between the line connecting the midpoint of the vertebral body of C7 to the midpoint of the superior endplate of S1 and the line connecting the center of the superior endplate of S1 to the midpoint between the femoral heads.
1-C Spinosacral angle (SSA): the angle between the line connecting the midpoint of the vertebral body of C7 to the midpoint of the superior endplate of S1 and the line parallel to the superior endplate of S1.

When analyzing sagittal spinal alignment, it is crucial to recognize compensation mechanisms. To counteract malalignment, the human body recruits these involuntary mechanisms to maintain an erect posture and horizontal gaze in an economically efficient manner. Compensation can occur in the spine, pelvis and/or lower limb.[32] In the thoracolumbar spine, TK could be reduced by hyperextension when the spine is still flexible, mostly observed in patients younger than 45.[33] One of the most important mechanisms is a posterior rotation of the pelvis around the femoral heads (pelvic retroversion, measured with PT), which means hyperextension of the hip joints, effectively.[34] Further compensation in the lower limbs can be seen as knee flexion and/or ankle extension.[35]

Various researchers assessed radiographic sagittal alignment in asymptomatic volunteers to describe the normal variety, which is striking and ranges from almost straight to heavily curved spines.[34,36-38] Roussouly et al. quantified and classified these variations into four types based on sacral tilt and lumbar lordosis.[39] This classification was later updated with a fifth subtype with an anteverted pelvis (Figure 2).[40] An overview of normal ranges of the spinopelvic parameters is given in Table 1.

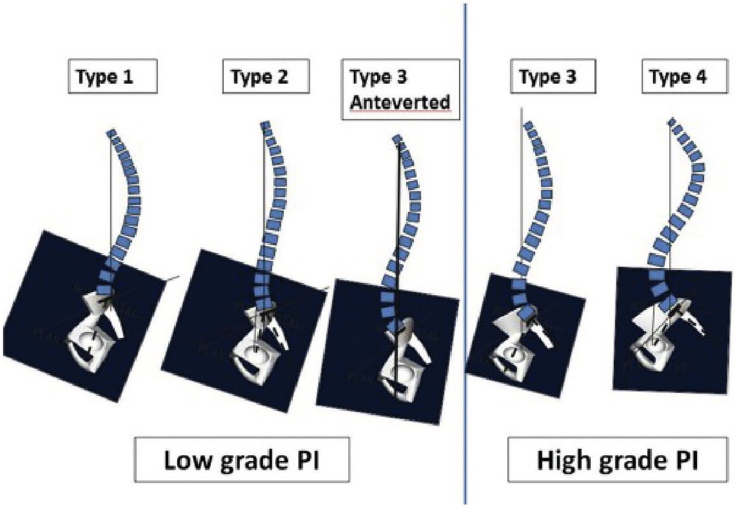

Figure 2. Updated Roussouly classification integrating the anteverted pelvis shape. Reproduced from Laouissat F et al. Classification of normal sagittal spine alignment: refounding the Roussouly classification. Eur Spine J. 2018 Aug;27(8):2002-2011.[40]

Table 1. Overview of normal range of spinopelvic parameters.

Spinopelvic parameter	Normal range
Cervical lordosis (CL)	20° – 40°
Thoracic kyphosis (TK)	20° – 50°
Lumbar lordosis (LL)	40° – 60°
Sagittal vertical axis (SVA) / C7 plumb line (C7pl)	-2 – 5 cm
T1 pelvic angle (TPA)	0° – 20°
Spinopelvic angle (SPA)	145° – 155°
Spinosacral angle (SSA)	130° – 140°
Pelvic incidence (PI)	45° – 65°
Sacral slope (SS)	30° – 50°
Pelvic tilt (PT)	5° – 20°

Treatment of mechanical pathologies of the spinal column

Spinal osteotomies have been the golden standard for the treatment of ASD for many years. Historically, spinal osteotomies were first performed in cases of ankylosing spondylitis (AS). This chronic inflammatory condition described by Vladimir Bechterew in 1892 affects the spine and sacroiliac joints, leading to stiffness and complete ossification of the vertebrae, usually with severe kyphosing deformity as a result.[41] Since then, many researchers studied the results of spinal osteotomies.[42-48] Nowadays, there are four main types of osteotomies: Smith-Peterson osteotomy (SPO)[49], pedicle subtraction osteotomy (PSO)[50], bone-disc-bone osteotomy (BDBO)[51] and vertebral column resection (VCR)[52]. These procedures are highly effective in restoring sagittal alignment, but PSO and VCR are especially associated with a high complication risk (up to 78%).[53-56] The reported complication rates for BDBO (30-50%)[51,57] and SPO (10-20%)[58] are much lower, although still relatively high.

Regional lumbar diseases, such as DDD or degenerative spondylolisthesis, are usually characterized by loss of LL and will lead to sagittal malalignment. When conservative treatment fails, spinal fusion could be indicated. In the early 20th century, Hibbs and Albee were the first to perform and describe a spinal fusion procedure by fusing the posterior elements of the spine using bone grafts, later termed posterolateral fusion (PLF).[59] In 1953, Cloward was the first to introduce the posterior lumbar interbody fusion (PLIF). This differs from the earlier techniques in that it focuses on direct fusion at the intervertebral disc spaces instead of the posterior elements.[60] A few decades later, the intervertebral body cage was introduced to improve the stabilization of the spine and promote fusion.[61,62] Another theoretical advantage of lumbar interbody fusion (LIF) over PLF, especially when a cage is used, is the possibility of restoring disc height and thus the LL.[63] After the original posterior approach, several other surgical approaches have been developed, including anterior (ALIF), transforaminal (TLIF), extreme/lateral (XLIF) and the more psoas muscle sparing techniques such as the oblique (OLIF) approach and the anterior to psoas (ATP) technique.[64-66] These techniques decrease the dissection of spinal and paraspinal muscles and may entail less nerve retraction than the posterior approach.[67]

Challenges in the treatment of sagittal spinal malalignment

Surgical correction of sagittal spinal malalignment is very challenging. High incidence rates of complications, including proximal junctional kyphosis (PJK, 39%), intraoperative blood loss (27%), nonunion (24%), neurologic deficit (18%), implant failure (13%) and intraoperative cerebrospinal fluid leak (12%) are reported.[68-75] Besides neurologic deficit, PJK, defined as kyphosis greater than 10° between the upper instrumented vertebra and the vertebral body two levels above, and nonunion are the most common and severe postoperative complications.[73] Several risk factors for developing PJK and nonunion have been identified, such as patient age, osteoporosis and inadequate (both under- and over-) correction of sagittal malalignment.[74,76] These complications represent the primary cause of revision surgery because of severe pain, potential compromise of neural components or further progression of the deformity.[77] Consequently, excellent alignment may prevent these complications. Therefore, the Global Alignment and Proportion (GAP) score was developed,[78] which proved more appropriate for predicting mechanical failure than the Schwab classification.[79] This clinical tool guides surgeons in preoperative planning by evaluating a patient's spinal alignment based on the individual PI. As a result, the optimal correction to achieve excellent alignment can be predicted. However, it is often a challenge to achieve that optimal correction due to technical limitations. This can result in persistent postoperative malalignment, which may lead to PJK and necessitate revision surgery. This domino effect poses increasing challenges with each successive revision surgery, with a reported recurrence rate of PJK as high as 47%[80] and an overall heightened risk of complication[81]. An alternative approach may be to correct the sagittal malalignment at the level of the pelvis. Performing an osteotomy between the sacral endplate and the femoral heads may reduce the PI. This approach could be particularly beneficial when the degree of LL correction required exceeds the capacity of an extended lumbar osteotomy or in complex revision cases. Furthermore, it was shown that lower-level osteotomies result in better sagittal profile correction,[82-84] highlighting the promising potential of a pelvic osteotomy.

Aim of the thesis

This thesis aims to evaluate the effectiveness of surgical treatment options for correcting sagittal spinal malalignment based on patient-reported outcomes and investigate how this knowledge is applied within the surgical community. Additionally, it explores pelvic osteotomies as a potentially less invasive alternative to spinal correction osteotomies. Various concepts of such a pelvic osteotomy were simulated in both in-silico and cadaveric setups.

THESIS OUTLINE

This thesis is divided into three parts. The first part (**Chapter 2-3**) examines the current state of evidence regarding the clinical relevance of sagittal spinal alignment. The second part (**Chapter 4-6**) discusses treatment options for sagittal malalignment. The third part (**Chapter 7-8**) provides a summary and general discussion.

The following research questions were formulated for this thesis:

Part I: Current evidence
Is there a correlation between surgically corrected sagittal alignment of the spine and patient-reported outcomes measurements in patients with lumbar degenerative disorders?
Although there is little evidence that surgical restoration of sagittal malalignment of the spine improves patient-reported outcomes, spinal alignment analysis has become more important in treatment decisions. In **Chapter 2**, a meta-analysis and systematic review of the literature were conducted to assess the correlation between patient-reported outcomes and achieved sagittal alignment of the spine in patients with lumbar degenerative disorders.

What is the current practice and influence of the sagittal alignment of the spine on the decision-making among spine surgeons in the Netherlands?
The recognition of the sagittal alignment of the spine is increasing. Therefore, the influence of spinal parameters on decision-making in the clinical practice of spine surgeons in the Netherlands was expected to become increasingly important. **Chapter 3** presents the results of a survey among spine surgeons in the Netherlands about the current influence on decision-making.

Part II: Surgical treatment options
Which posterior surgical technique is most appropriate to achieve adequate lumbar lordosis restoration in patients with degenerative disorders?
A decrease in lumbar lordosis is, among other characteristics, found in degeneration of the lumbar spine and affects the overall alignment and biomechanics of the spine. As opposed to PLF, LIF has the advantage of restoring the disc height, lengthening the anterior column and therefore, restoring LL. The contribution of each different step of a posterior approach restoring lordosis with a posteriorly inserted cage was tested in an experimental setup presented in **Chapter 4**.

Is a bilateral anterior open-wedge correction osteotomy of the ilium effective in changing the pelvic incidence (PI) to correct sagittal malalignment of the spine?
Pelvic morphology is increasingly recognized as a regulator of global spinal alignment. Because extensive lumbar correction osteotomies posteriorly shortening the spine to

correct the decrease of lumbar lordosis are associated with many complications, an alternative could be a bilateral anterior open-wedge correction osteotomy of the ilium (named as bilateral extending pelvic osteotomy [BEPO]). In **Chapter 5**, the anatomical effects of this procedure on PI were quantified in a human cadaveric study.

What is the feasibility of different pelvic dome osteotomies compared to an open wedge pelvic osteotomy when tested in an in-silico model?
A pelvic dome osteotomy (DPO) could be a feasible alternative for an open-wedge pelvic osteotomy to provide a more predictable and stable situation. In an in-silico model study, several essential outcome measurements can be tested. **Chapter 6** focuses on the potential pelvic extension, bone contact surface area, the effect on the length of the sacropelvic ligaments and global sagittal balance after BEPO and DPOs around the sacral endplate, the sacroiliac joints and the two acetabular centers.

Part III: Summary and general discussion
Finally, **Chapter 7** provides a general discussion of this thesis's findings, including an overall conclusion and future perspectives. **Chapter 8** provides a summary in Dutch.

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I

CURRENT EVIDENCE

2

Surgical restoration of sagittal alignment of the spine: correlation with improved patient-reported outcomes: a systematic review and meta-analysis

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Abstract

Introduction The sagittal plane curvatures of the human spine are the consequence of evolution from quadrupedalism to bipedalism and are needed to maintain the center of mass of the body within the base of support in the bipedal position. Lumbar degenerative disorders can lead to a decrease in lumbar lordosis and thereby affect the overall alignment of the spine. However, there is not yet enough direct evidence that surgical restoration of spinal malalignment would lead to a better clinical outcome. Therefore, this study aims to assess the correlation between patient-reported outcomes and actual obtained sagittal spinal alignment in adult patients with lumbar degenerative disorders who underwent surgical treatment.
Materials and methods A comprehensive literature search was conducted through databases (PubMed, Cochrane, Web of Science, and Embase). The last search was in November 2018. The risk of bias was assessed with the Newcastle-Ottawa quality assessment scale. A meta-regression analysis was performed.
Results Of 2,024 unique articles in the original search, 34 articles with 973 patients were included. All studies were either retrospective or prospective cohort studies; no randomized controlled trials were available. A total of 54 relations between preoperative-to-postoperative improvement in patient-reported outcome measures (PROMs) and radiographic spinopelvic parameters were found, of which 20 were eligible for meta-regression analysis. Of these, two correlations were significant: pelvic tilt (PT) versus Oswestry Disability Index (ODI) ($p = 0.009$) and PT versus visual analog scale (VAS) pain ($p = 0.008$).
Conclusions Based on the current literature, lower PT was significantly correlated with improved ODI and VAS pain in patients with sagittal malalignment caused by lumbar degenerative disorders that were treated with surgical correction of the sagittal balance.

Introduction

The curvatures of the human spine are unique compared with other species. As a result of evolution from quadrupedalism to bipedalism, only humans developed sagittal curvatures to maintain the head straight above the pelvis in a bipedal position. These curves were first described by Hippocrates (460-370 BCE) as *ithiscolios*, indicating the spine is curved in the sagittal plane but straight in the coronal plane.[1]
In cases of spinal pathology affecting the spinal curvatures as a whole, such as severe idiopathic adolescent scoliosis or ankylosing spondylitis, surgical correction of the spine is crucial to prevent loss of pulmonary function or a forward-stooped posture later in life. The spinal curvatures can also be influenced by segmental or short trajectory spinal pathology such as degenerative disc disease, vertebral fracture, infection and malignancy. Because of local deformity and compensatory postural changes, spinal equilibrium (referred to below as sagittal spinal alignment) can be affected.
For many years, spinal surgeons were mainly focused on local treatment of spinal pathology without regard to overall spinal alignment. Current treatment guidelines for lumbar degenerative disorders, affecting up to 60% of the aging adult population,[2] focus on patient-reported outcomes measurements (PROMs) that are assessed by pain, disability and health-related quality of life (HRQOL) measurements. However, these PROMs are influenced by the balance of the entire spine. With the increasing awareness of the importance of spinopelvic parameters for the proper functioning of the spinal column, many spinal surgeons have adopted the assumption that restoration of this alignment would lead to a better clinical outcome.[3-11] However, there is little evidence that surgical restoration of sagittal spinal alignment improves PROMs.
The aim of this study was to assess the correlation between PROMs and achieved sagittal alignment of the spine in patients with lumbar degenerative disorders.

Materials and Methods

This meta-analysis and systematic review methodology was designed according to common guidelines for systematic reviews such as those given in the Cochrane Handbook. Reporting was structured according to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) statement.[12]
The primary aims of this study were (1) to assess the correlation between PROMs and actual obtained sagittal spinal alignment in adult patients with lumbar degenerative disorders who underwent surgical treatment and (2) to give an overview of the measurements that are used to measure sagittal alignment of the spine.

Search strategy
The PubMed, Cochrane, Web of Science and Embase databases were searched on November 1, 2018, and reference lists of included studies were checked for additional studies. The search strategy for PubMed is reported in Table 1 and the search strategy for the other databases was adapted to the specific database requirements. The results of the search were exported to a database (RefWorks 2.0; ProQuest) and all duplicate entries were identified and removed.

Table 1. Search strategy in PubMed

Dimension	Search string
Sagittal alignment	((((“sagittal balance”[tiab] OR “sagittal imbalance”[tiab] OR “sagittal alignment”[tiab] OR “sagittal malalignment”[tiab] OR “C7 plumb line”[tiab] OR “sagittal vertical axis”[tiab] OR “pelvic tilt”[tiab] OR “sacral slope”[tiab] OR “sacral tilt”[tiab] OR “pelvic incidence”[tiab] OR “spinopelvic parameters”[tiab] OR “pelvic parameters”[tiab]))))
Outcome	((HR-PRO[tiab] OR HRQL[tiab] OR HRQoL[tiab] OR QL[tiab] OR QoL[tiab] OR quality of life[tw] OR life quality[tw] OR health index*[tiab] OR health indices[tiab] OR health profile*[tiab] OR health status[tw] OR ((patient[tiab] OR self[tiab] OR child[tiab] OR parent[tiab] OR carer[tiab] OR proxy[tiab]) AND ((report[tiab] OR reported[tiab] OR reporting[tiab]) OR (rated[tiab] OR rating[tiab] OR ratings[tiab]) OR based[tiab] OR (assessed[tiab] OR assessment[tiab] OR assessments[tiab]))) OR ((disability[tiab] OR function[tiab] OR functional[tiab] OR functions[tiab] OR subjective[tiab] OR utility[tiab] OR utilities[tiab] OR wellbeing[tiab] OR wellbeing[tiab]) AND (index[tiab] OR indices[tiab] OR instrument[tiab] OR instruments[tiab] OR measure[tiab] OR measures[tiab] OR questionnaire[tiab] OR questionnaires[tiab] OR profile[tiab] OR profiles[tiab] OR scale[tiab] OR scales[tiab] OR score[tiab] OR scores[tiab] OR status[tiab] OR survey[tiab] OR surveys[tiab]))) OR PROM[tiab] OR PROMs[tiab])

Study selection
Two reviewers independently performed selection with discrepancies resolved by a consensus meeting, including a referee if necessary. Studies were selected based on the following criteria:

1. Studies: both prospective and retrospective cohort studies were eligible. No minimum follow-up was required.
2. Types of patients: studies on surgically treated patients with lumbar degenerative disorders (degenerative disc disease, degenerative lumbar scoliosis, degenerative spondylolisthesis) and adult spinal deformity (ASD) were included.
3. Types of outcome measurements: preoperative and postoperative clinical outcomes and radiographic measurements were required.

Primary outcomes that were included were (1) spinopelvic radiological parameters (Figure 1) and (2) PROMs. The PROMs included, but were not limited to, Oswestry Disability Index (ODI)[13], Japanese Orthopedic Association (JOA) score[14], Scoliosis Research Society (SRS) score[15], Short Form (SF) Health Survey[16], Roland-Morris Disability Questionnaire (RMDQ)[17], EuroQol-5 dimensions (EQ-5D) health questionnaire[18] and Visual Analogue Scale (VAS) for pain[19]. Full-text articles were retrieved if a reference could not be excluded based on the title and abstract.

Quality assessment
The risk of bias was assessed with the Newcastle-Ottawa quality assessment scale.[20] The risk of bias was considered low if studies met at least 50% of the items.

Data extraction
Selected data were imported into Excel 2020 (Microsoft) for further processing. The extracted data included the first author, year of publication, sample size, design (prospective or retrospective), follow-up period, diagnosis, intervention, postoperative radiographic measures and PROMs, including the corresponding standard deviation. For articles with missing data, the corresponding authors were contacted and three attempts were made to collect as much information as possible.

Analysis
Synthesis was performed on the outcome (correlation) level, integrating the results from different studies reporting identical types of correlations. A pooled correlation coefficient was calculated, indicating the heterogeneity. In this synthesis, the quality, consistency and precision of the evidence were taken into account together with the probability of publication bias and indirectness of evidence as well as the quality of evidence.[21] Random-effects meta-analysis was conducted using the metan package in Stata (StataCorp).[22] Pooling was performed after Fisher z transformation of the correlation coefficient; the standard error was calculated as 1/sqrt(n3-). Back-transformed correlations and their confidence intervals are also reported.

Results

Search results
The flow chart for the search and selection process is shown in Figure 2. Out of 2,024 articles in the original search, 1,979 articles had to be excluded. Checking the reference lists yielded two additional relevant articles, which were included. In total, 47 articles were selected for further review and 13 were excluded because of missing data. The remaining 34 articles[5,9,23-54], describing 973 patients, were included in this meta-analysis. All studies were either retrospective or prospective cohort studies; the average Newcastle-Ottawa quality assessment scale was 77% and 29% were considered at low risk of bias. The mean follow-up was 28.4 months (range 6 to 75.6

months). Tables 2, 3 and 4 report the characteristics of the included studies, the number of correlations and the quality of evidence (as assessed by the Newcastle-Ottawa Scale), respectively.

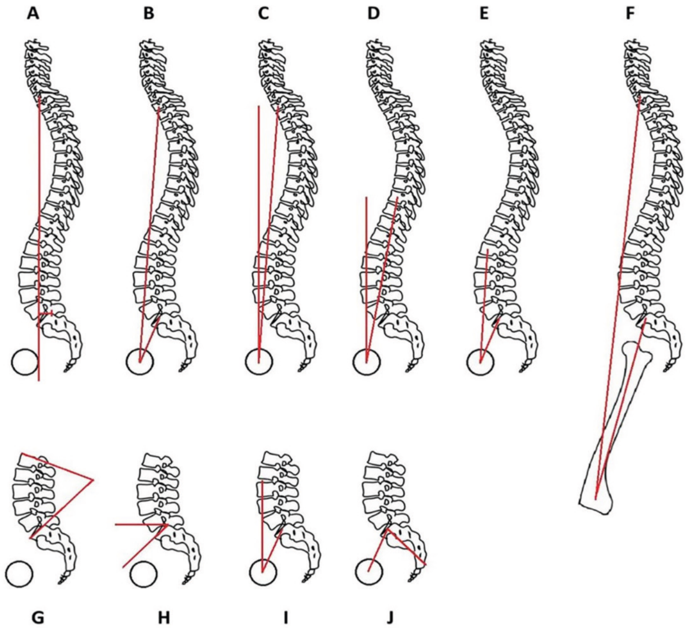

Figure 1. Overview of spinopelvic radiological parameters**.**
1-A Sacral vertical axis (SVA)/ C7 plumb line (C7pl): the distance between the plumb line from the vertebral body center of C7 and the posterosuperior corner of the superior endplate of S1. **1-B** T1 pelvic angle (TPA): the angle between the line connecting the midpoint from the vertebral body center of Th1 to the midpoint between the femoral heads and the line connecting the center of the superior endplate of S1 to the midpoint between the femoral heads. **1-C** Th1-spinopelvic inclination (T1-SPi): the angle between the line connecting the vertebral body center of Th1 to the midpoint between the femoral heads and a vertical line. **1-D** Th9-spinopelvic inclination (T9-SPi): the angle between the line connecting the vertebral body center of Th9 to the midpoint between the femoral heads and a vertical line. **1-E** Lumbo-femoral angle (LFA): the angle between the line connecting the center of the superior endplate of S1 to the midpoint between the femoral heads and the line connecting the center of the superior endplate of L1 to the midpoint of the femoral heads. **1-F** Global sagittal axis (GSA): the angle between the line connecting the midpoint between the 2 distal femoral condyles to the vertebral body center of C1 and the line connecting the midpoint between the 2 distal femoral condyles to the posterosuperior corner of the superior endplate of S1. **1-G** Lumbar lordosis (LL): the angle between the superior endplate of L1 and the superior endplate of S1. **1-H** Sacral slope (SS): the angle between the superior endplate of S1 and a horizontal line. **1-I** Pelvic tilt (PT): the angle between the line connecting the center of the superior endplate of S1 to the midpoint between the femoral heads and a vertical line. **1-J** Pelvic incidence (Pl): the angle between the line perpendicular to the endplate of S1 and the line connecting the center of the superior endplate of S1 to the midpoint between the femoral heads.

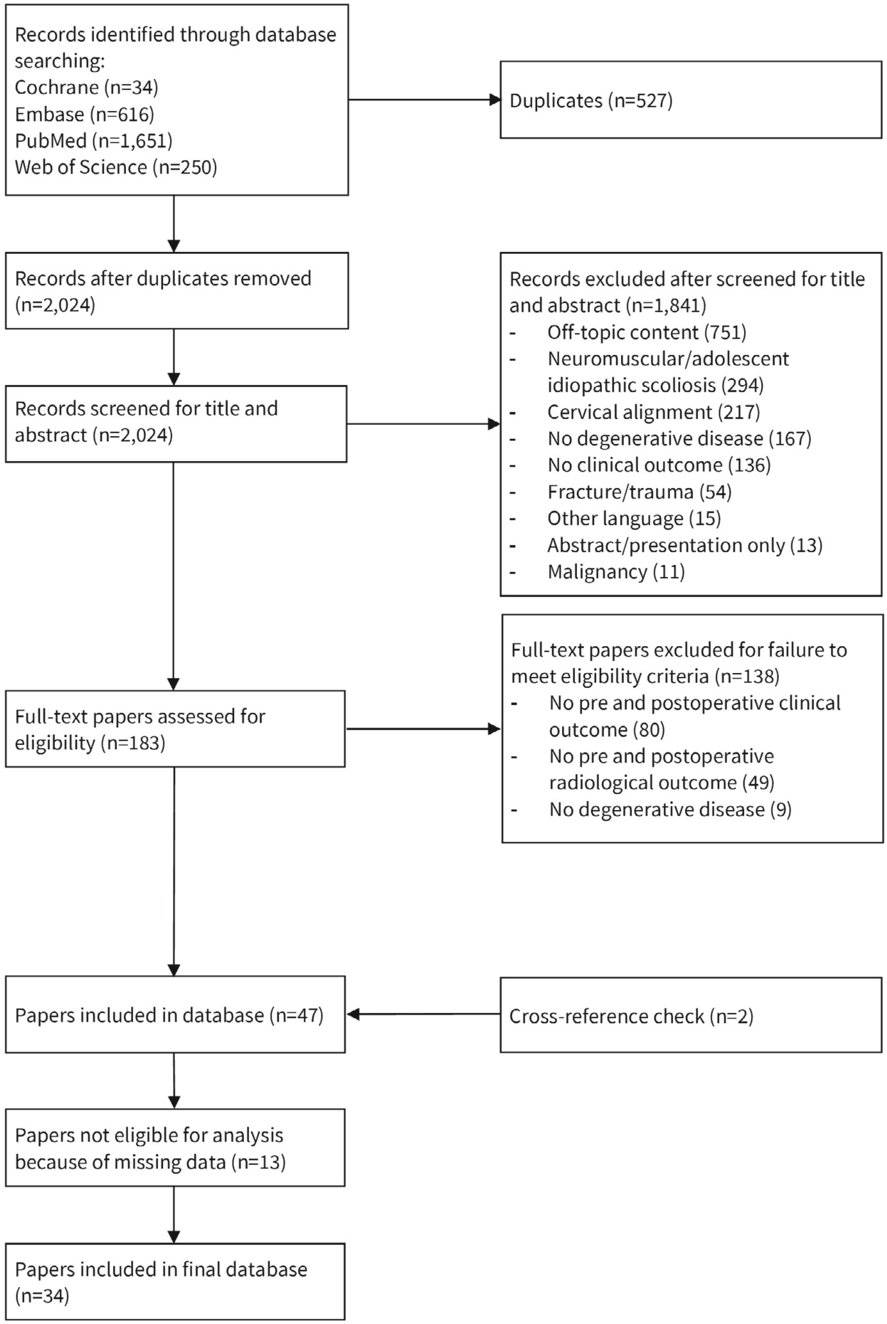

Figure 2. Flow diagram for the search strategy.

Table 2. Characteristics of included studies*

Author	Year	Sample size	Design	FU (m)	Diagnosis	Intervention	Radiographic outcome	PROM
Alimi[23]	2014	90	retrospective	12.6	Lumbar DDD	XLIF	PI-LL	ODI, VAS
Aoki[24]	2015	52	prospective	16.9	Lumbar DDD	Short-segment TLIF	PI-LL	ODI, VAS
Ayhan[25]	2016	121	prospective	12	Lumbar DDD	SPO/PSO	SVA, PT, LL	ODI, SF36, SRS22
Blondel[26]	2011	76	retrospective	24	ASD	Spinal fusion	SVA	ODI, SRS30, SF12
Bourghli[27]	2017	164	retrospective	24	ASD	Posterior fusion	SVA, PI-LL, PT, LL	ODI, SF36, SRS22
Chang[28]	2017	55	retrospective	55	Lumbar DDD	PSO	SVA, PT, LL	ODI, VAS
Cho[29]	2008	50	retrospective	51.6	Degenerative lumbar scoliosis	Posterior fusion	SVA, LL	ODI
Cho[30]	2017	88	retrospective	24	Lumbar DDD	24	SVA, PT, LL	ODI, EQ-5D, VAS
Cogniet[31]	2016	63	prospective	23.5	Degenerative lumbar scoliosis	PSO	SVA, PT, LL. SS	ODI, SF36, VAS
Demirkiran[32]	2016	8	retrospective	18.4	ASD	ACR	SVA, PT, LL	ODI, EQ-5D
Du[33]	2015	43	retrospective	27.6	ADS	Posterior fusion	SVA, PT, LL	ODI

Table 2. Characteristics of included studies* *(continued)*

Author	Year	Sample size	Design	FU (m)	Diagnosis	Intervention	Radiographic outcome	PROM
Endo[34]	2010	61	retrospective	6	Lumbar disc herniation	Hemiectomy	SVA, LL	JOA
Farrokhi[35]	2018	88	prospective	24	Degenerative lumbar stenosis	PLIF	SVA, PT, LL	ODI, VAS
Fujii[36]	2015	88	retrospective	1.28	Degenerative lumbar stenosis	Lumbar decompression	SVA, PI-LL, PT, LL	VAS
Hikata[37]	2015	109	retrospective	30	Degenerative lumbar stenosis	Lumbar decompression	SVA, PT, LL	RMDQ, JOA, VAS
Hosseini[38]	2017	39	retrospective	13.3	ASD	ALIF	SVA, PI-LL, PT, LL, T1SPi	ODI, SRS22, VAS
Hyun[39]	2010	13	retrospective	36	Degenerative sagittal imbalance	PSO	SVA, LL	ODI
Kawakami[5]	2002	47	retrospective	?	Degenerative lumbar spondylolisthesis	Posterior spinal fusion	LL	JOA
Kim[40]	2011	18	retrospective	24	Degenerative lumbar spondylolisthesis	Posterior interbody fusion	SVA, PT, LL, SS	ODI, VAS
Kim[41]	2016	32	retrospective	75.6	ASD	Posterior fusion	SVA, PI-LL, PT, LL	ODI, SRS22
Lazennec[42]	2014	46	prospective	24	Lumbar DDD	Total disc replacement	PT, LL	ODI, VAS

Table 2. Characteristics of included studies* *(continued)*

Author	Year	Sample size	Design	FU (m)	Diagnosis	Intervention	Radiographic outcome	PROM
Lee[43]	2016	70	retrospective	72	Lumbar DDD	TLIF	SVA, PT, LL	ODI, VAS
Louie[44]	2018	25	retrospective	34.8	Lumbar DDD	LLIF	PI-LL, LL	ODI, VAS
Marchi[45]	2012	8	retrospective	24	Lumbar DDD	ALIF	SVA, PT, LL	ODI, VAS
Massie[46]	2018	39	retrospective	18	Degenerative spondylolisthesis	TLIF	SVA, PI-LL, PT, LL	ODI, VAS
Park[47]	2015	105	retrospective	31.3	ASD	Posterior fusion	SVA, PI-LL, PT, LL	ODI, VAS
Rose[48]	2009	40	retrospective	24	ASD	PSO	SVA, LL	ODI, SRS22
Schwab[49]	2013	177	prospective	12	ASD	Posterior fusion	SVA, PI-LL, PT	ODI, SRS, SF36
Smith[9]	2015	227	retrospective	24	ASD	Deformity surgery	SVA, PI-LL, PT, LL	ODI, SRS22, SF36
Sun[50]	2017	74	retrospective	38.4	ASD	Posterior fusion	PI-LL, LL	ODI, JOA, VAS

Table 2. Characteristics of included studies* *(continued)*

Author	Year	Sample size	Design	FU (m)	Diagnosis	Intervention	Radiographic outcome	PROM
Than[51]	2017	76	retrospective	33.5	ASD	Posterior fusion	SVA, PI-LL, PT, LL	ODI, VAS
Yang[52]	2015	56	retrospective	?	Degenerative scoliosis	Posterior fusion	LL	ODI, VAS
Yasuda[53]	2017	56	prospective	?	ASD	Posterior fusion	SVA, PI-LL, PT, LL	ODI
Zou[54]	2014	68	retrospective	7.9	Degenerative scoliosis	Posterior instrumentation	SVA, PT, LL, SS	ODI

*DDD = degenerative disc disease, XLIF = extreme lateral interbody fusion, TLIF = transforaminal lumbar interbody fusion, SPO = Smith-Petersen osteotomy, PSO = pedicle subtraction osteotomy, ACR = anterior column release, ASD = adult spinal deformity, PLIF = posterior lumbar interbody fusion and ALIF = anterior lumbar interbody fusion.

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Table 3. Number of manuscripts reporting correlations between PROMs and radiographic outcomes

Radiographic outcome	PROM	No.
SVA	ODI	23
	JOA	3
	SRS	13
	SF-12	1
	SF-36	8
	RMDQ	1
	EQ-5D	1
	VAS	8
PI-LL	ODI	15
	JOA	1
	SRS-22	8
	SF-36	4
	EQ-5D	1
	VAS	6
PT	ODI	15
	JOA	1
	SRS-22	9
	SF-12	4
	SF-36	3
	EQ-5D	1
	VAS	4
LL	ODI	11
	JOA	2
	SRS-22	4
	SF-12	4
	SF-36	1
	VAS	4
TPA	ODI	5
	SRS-22	4
	SF-12	1
	SF-36	2
	EQ-5D	1
	VAS	1

Table 3. Number of manuscripts reporting correlations between PROMs and radiographic outcomes *(continued)*

Radiographic outcome	PROM	No.
T1SPi	ODI	5
	SRS-22	3
	SF-12	2
	SF-36	1
SS	ODI	7
	SRS	2
	SF-12	2
	SF-36	1
	VAS	3
T9SPi	ODI	3
	SRS	1
	SF-12	1
GSA*	ODI	1
	SRS-22	1
	EQ-5D	1
	VAS	1
LFA	ODI	1
	SF-36	1
	VAS	1

*GSA = global sagittal axis

Table 4. Quality of evidence as assessed by the Newcastle-Ottawa Scale (NOS)

	Selection	Comparability	Outcome	Total (%)
Alimi[23]	3	2	3	89
Aoki[24]	3	2	2	78
Ayhan[25]	3	2	3	89
Blondel[26]	4	2	3	100
Bourghli[27]	4	2	2	89
Chang[28]	3	1	4	89
Cho (2008)[29]	2	2	2	67
Cho (2017)[30]	4	2	2	89
Cogniet[31]	4	1	3	89
Demirkiran[32]	3	2	2	78
Du[33]	3	2	2	78
Endo[34]	3	1	0	44
Farrokhi[35]	2	1	3	67
Fujii[36]	3	2	2	78
Hikata[37]	3	2	1	78
Hosseini[38]	3	2	1	67
Hyun[39]	4	1	2	67
Kawakami[5]	4	1	2	78
Kim (2011)[40]	4	1	3	89
Kim (2016)[41]	3	1	3	78
Lazennec[42]	4	1	2	78
Lee[43]	4	1	3	89
Louie[44]	4	1	2	78
Marchi[45]	4	1	2	78
Massie[46]	4	1	3	89
Park[47]	2	1	3	67
Rose[48]	4	1	0	56
Schwab[49]	4	1	0	56
Smith[9]	3	1	3	78
Sun[50]	2	1	3	67
Than[51]	3	1	2	67
Yang[52]	4	1	2	78
Yasuda[53]	4	1	2	78
Zou[54]	3	2	2	78

Outcomes

The primary aim of this study was to assess the correlation between PROMs and actual obtained sagittal spinal alignment in adult patients with lumbar degenerative disorders who underwent surgical treatment. Nine different PROMs were used (ODI, SF-12 or 36, SRS-22 or 30, EQ-5D, RMDQ, JOA and VAS) as the clinical outcome in the included studies. The ODI was used in 88% (all but four[5,34,36,37]) of the articles. The ranges and minimal clinically important differences (MCIDs) were obtained from the literature.[14,55-58] Improvement exceeding the MCID was found for most (89%) of the studies; for the ODI, 97% (all but one[46]) of the studies reported improvement exceeding the MCID.

A meta-regression analysis was performed to assess the correlations. A total of 54 relations between preoperative to postoperative improvement of PROMs and radiological spinopelvic parameters were found in the included articles. Despite several attempts to obtain missing data from the corresponding authors, this yielded no additional useful data. The data sets of 13 manuscripts were not eligible for our regression analysis because these were incomplete. Furthermore, several relationships between certain PROMs (SRS, SRS30, SF12, RM and EQ5D) and any radiographic outcome measure were reported only once in the included articles and could therefore not undergo meta-regression analysis. In total, 20 relations were available for analysis (Table 5). Of these, two had significant correlations: lower postoperative pelvic tilt (PT) was correlated with a lower ODI ($p = 0.009$) and lower PT was related to less pain ($p = 0.008$).

The secondary aim of this study was to assess the radiological measurements that are used to measure the sagittal alignment of the spine. The sagittal vertical axis (SVA) was the most frequently used (27 [79%] of the studies). This parameter is used interchangeably with the C7 plumb line. In total, data of five radiographic parameters (lumbar lordosis [LL], pelvic incidence [PI]-LL mismatch, PT, sacral slope [SS] and SVA) were eligible for the regression analysis and the only significant relationships were for PT versus HRQOL and pain. The global angular measurements, such as spinopelvic angle and T1 pelvic angle (TPA), could not be analyzed in the meta-regression because these were used only in one study.

Table 5. meta-regression analysis*

	EQ5D	JOA	ODI	RMDQ	SF-12	SF-36	SRS-22	SRS-30	VAS
LL	†	NS (-1.592 to 0.832)	NS (-0.172 to 0.365)	‡	†	NS (-0.662 to 0.662)	NS (-0.237 to 0.196)	†	NS (-0.335 to 0.500)
PI-LL	†	‡	NS (-0.541 to 0.628)	†	†	NS (-9.544 to 8.777)	NS (-0.757 to 0.639)	†	NS (0.669 to 1.419)
PT	†	‡	0.009 (0.321 to 1.986)	‡	†	NS (-1.963 to 2.109)	0.131 (-0.369 to 0.098)	†	0.008 (0.455 to 2.586)
SS	†	†	NS (-2.023 to 3.002	†	†	†	‡	†	NS (-1.230 to 2.742)
SVA	†	NS (-0.389 to 0.556)	NS (-0.132 to 0.11)	‡	‡	NS (-0.132 to 0.236)	NS (-0.040 to 0.051)	‡	0.068 (-0.020 to 0.484

*The values are given as the p value, with the 95% confidence interval of the regression coefficient in parenthesis. NS = not significant (> 0.20). † No analysis possible; <1 observation. ‡ No analysis possible, a single study.

Discussion

This systematic review and meta-analysis found low-quality evidence that surgical correction of spinopelvic parameters may lead to a better clinical outcome. However, since the studies are not controlled trials, serious biases such as regression to the mean, patient selection and placebo effects make the findings difficult to value. In addition to the low-quality evidence, the articles could demonstrate only associations and not causality since they were not randomized trials. Unfortunately, all of the included studies were observational, and in some studies, correction of sagittal malalignment was not the primary aim; it was a side-effect of the surgery. This means that the correlation could be confounded by other conditions that were treated, such as painful spondylolisthesis. On the other hand, the results of the regression analysis indicated a correlation between lower PT and decreased disability and pain (ODI and VAS), suggesting a causal relationship. This meta-analysis therefore constitutes the current best, although still not strong, evidence of a correlation between improved spinopelvic parameters after surgical correction and improved clinical outcome. However, even with our extensive search and data analysis, only a minority of the correlations between PROMs and radiographic parameters were significant.

Many parameters have been used to describe the sagittal alignment of the spine on radiographic assessments and new parameters are still being added. Although it is cumbersome because of its need for calibration,[59] the SVA is the most used parameter to measure sagittal alignment, both in this study (79% of the included articles) and in the recent literature. Newer parameters such as the TPA, Th1/Th9 spinopelvic inclination (T1-SPi/T9-SPi) and lumbofemoral angle (LFA) have been proposed to obviate the need for calibration by angular measurements.[60-63] Even more recently, the C2 incidence (C2I) angle and parameters using the midline of the skull as a reference point to analyze global spinal alignment have been described.[64] However, none of the studies that used these newer parameters could be included in the regression analysis due to missing data and we were therefore unable to assess their correlation with PROMs.

In an earlier study by Glassman et al., an SVA > 5mm was associated with decreased HRQOL.[65] More recently, there has been an increasing understanding of age-adjusted normative values for SVA and other spinopelvic parameters. Iyer et al. studied 115 healthy volunteers and found a relatively strong correlation between increased SVA and age ($r = 0.46$, $p < 0.001$) without increased back pain and disability.[11] However, acknowledging compensating mechanisms is crucial in evaluating sagittal spinal alignment. The reciprocal association among pelvic parameters has a key role in the evaluation of these mechanisms. Because of the minimal motion that is possible in the sacroiliac joint, PI, PT and SS can be mathematically linked by the formula: $PI=PT+SS$.[66] Although PI increases slightly during growth, it remains relatively constant during adulthood.[67] Pelvic retroversion (increase of PT and decrease of SS) is a compensatory mechanism that allows the patient to maintain a balanced

standing posture in which other radiological spinal parameters are within the normal range. Therefore, PT is a sensitive parameter to measure compensatory mechanisms in patients with sagittal malalignment. In this meta-analysis, PT was the only radiographic parameter that was found to be significantly correlated with a PROM: a decrease in PT was significantly related to improvements in ODI and VAS. This is consistent with the study by Lafage et al.,[7] in which an analysis of sagittal spinal alignment in non-surgically treated patients found PT to be correlated with SRS ($r = -0.29$) and ODI ($r = 0.30$). Although the correlations were weak to moderate, PT is essential to assess compensatory mechanisms and is therefore still a key element in the analysis of sagittal malalignment. The key nature of PT is even more evident in patients who are not able to achieve increased PT because of hip arthrosis and are therefore at significantly greater risk of an unbalanced sagittal spinopelvic alignment ($p < 0.05$).[68]
Preoperative planning of correction involves many factors, such as age and the patient's anatomy. Lafage et al. found that patients ≥75 years old still had an average ODI score of 20 despite a PI-LL mismatch of 8.3°, whereas younger patients (35 to 44 years old) with the same ODI score had a PI-LL mismatch of -2.7°.[69] On the other hand, correction of LL to within ±9° of PI is suggested by Schwab et al. as a rule of thumb for patients with flat-back deformity due to degenerative disorders.[49] In an attempt to better assess the spinopelvic parameters, including the proportion of the LL derived from L4-S1, the Global Alignment and Proportion (GAP) score was developed to predict adequate surgical restoration.[70] This allows the identification of patient-specific surgical goals and may result in better outcomes and prevent mechanical complications due to over- or undercorrection.

Limitations
The most significant limitations of our study are the quality of the included papers and the lack of data quantification. Many articles had to be excluded because clinical and/or radiographic outcome measurements were unavailable, even after multiple requests to the corresponding authors. Publication bias should also be considered, although the comprehensive search strategy in the present study tried to limit this.

Implications for further research
To conduct a randomized controlled trial comparing surgery aimed or not aimed at restoration of sagittal balance would be unethical. Prospective studies are therefore more feasible and may be as accurate as randomized controlled trials.[71] Authors should be encouraged to publish prospective cohort studies that compare clinical and radiographic outcome parameters during follow-up of surgical cases and a supplementary document with all data should be made available.
Angular measurements are less prone to bias than measurements that measure the distance between two points. Greater use of newer radiographic parameters may enable a better assessment of their relationships with PROMs. Also, standard outcome

measurements should be used to report clinical outcomes and correlations between these outcomes and radiographic parameters should be assessed and reported.

Conclusion

This systematic review of the literature and meta-analysis found a significant correlation between decreased PT, decreased ODI and VAS in surgically treated patients with lumbar degenerative disorders. Based on the currently available literature, this review provides the best, yet still low-quality, evidence for the effect of restoring alignment during surgery. To improve the quality of research, standard clinical outcome parameters should be used in future studies so that correlation analysis can be performed.

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Sagittal balance of the spine in daily practice: a survey among spine surgeons in the Netherlands

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Abstract

Purpose To provide an overview of the influence of the sagittal balance concept on diagnosis and decision-making among spine surgeons in the Netherlands.
Materials and methods A survey was conducted amongst members of the Dutch Spine Society, which includes both neurosurgeons and orthopedic surgeons. The survey posed questions concerning the application of the sagittal balance concept in clinical practice, diagnostic workup and its influence on decision-making and surgical outcome.
Results Among spine surgeons in the Netherlands, there is widespread support for the theory of the sagittal balance of the spine in clinical practice. Neurosurgeons apply it clinically less often and perform fewer diagnostics to determine the sagittal balance than orthopedic surgeons. When applied, for most respondents the sagittal balance concept influences clinical decision-making, but fewer think that it improves patients' outcomes.
Conclusions In the Netherlands, most spine surgeons are familiar with the theory of sagittal balance, but its clinical application thus far is limited, especially among neurosurgeons.

Introduction

Low back pain (LBP) is globally an important health problem as it is the number one cause of disability in modern society with huge subsequent indirect costs due to lost economic productivity.[1] LBP has a lifetime prevalence in the Netherlands as high as 60-90% in the general (/family) practice population[2] and up to 84% worldwide.[3] Degenerative spinal disorders are held responsible for most of the symptoms.[4] With aging, degenerative processes cause a decrease of lumbar lordosis (LL), thereby altering the balance of the spinal column in the sagittal plane.[5,6] Retroversion of the pelvis, hyperextension of the hip joints and flexion of the knees are physiological compensatory mechanisms to maintain the body in an upright posture.[7] This mechanism gradually loses its capacity to compensate because of further decrease of the lumbar lordosis and/or increase of the thoracic kyphosis, particularly due to loss of intervertebral disc heights.[8] These compensatory mechanisms increasingly cause low back pain because of overstress and facet constraints.[8] Conversely, the sagittal balance can be negatively influenced by spine surgery, such as vertebral fusion, as the vertebrae may have been fused with a decrease of the spinal curvature, leading to forward inclination of the trunk.[9-13] An elevated pelvic tilt (PT), reduced LL and sagittal malalignment are generally associated with poorer functional outcomes after surgery.[14] Spine surgeons increasingly recognize the importance of maintaining and improving the sagittal balance for a better clinical outcome. Accordingly, the influence of sagittal balance parameters on decision-making in clinical practice is increasing in the Netherlands. This study aimed to provide an overview of the current influence of the sagittal balance of the spine on the decision-making of spine surgeons in the Netherlands.

Material and Methods

A cross-sectional survey containing both multiple-choice and open questions was produced under the supervision of three spine surgeons (PW, SvG and CÖ). All members of the Dutch Spine Society (DSS), the professional organization of all spine surgeons in the country, both orthopedic surgeons and neurosurgeons, were invited to participate in the survey on paper on November 7, 2014, at the annual meeting of the society. Since not all members of the DSS were present at this meeting, the remaining members were approached by e-mail on November 15, 2014. This e-mail contained a unique link to an electronic version of the same survey. A final call for participation in the survey was made in the newsletter of the DSS, one month after the annual meeting. The surveys were completed anonymously.

Data analysis

The data from the completed surveys was entered into Microsoft Excel (Microsoft Corp., Redmond, Washington, USA). Statistical analyses were performed with

Statistical Package for the Social Sciences software (SPSS 22.0, SPSS Inc., Chicago, Illinois, USA).[15] The Fisher's exact test was employed to calculate the statistical significance of contingency tables.

Results

At the time of the survey, the DSS consisted of 178 members: 107 orthopedic surgeons (60%), 61 neurosurgeons (34%) and 10 non-surgeon members (6%). Of those, 81 members declared not to perform spinal fusion operations and were therefore excluded from the survey. Of the remaining 87 orthopedic and neurosurgeons, 60 (68.9%) completed the survey (43 orthopedic surgeons (72%), 17 neurosurgeons (28%)). The main characteristics of the participants are displayed in Table 1. Both neurosurgeons and orthopedic surgeons have comparable clinical experience and consider the theory of sagittal balance important (98% of orthopedic surgeons and 88% of neurosurgeons, $p=0.191$). However, orthopedic surgeons apply the theory of sagittal balance in clinical practice significantly more often (83.7% vs. 29.4%, $p < 0.0001$).
As displayed in Table 2, most specialists who consider the sagittal balance to be important also apply it in clinical practice. However, 10 of the 15 neurosurgeons who find the conceptual framework relevant do not apply it in clinical practice versus 7 of the 42 orthopedic surgeons who do find it relevant. (Remarkably, one neurosurgeon applies the sagittal balance concept in daily practice but does not find the theory relevant). Surgeons, who use the sagittal balance in clinical practice, perform radiological investigations of the spine and the physical examination of the hips significantly more often (Table 2) (both $p < 0.001$). Also, orthopedic surgeons perform radiological investigations through radiograms and physical examination of the hips significantly more often than neurosurgeons ($p < 0.001$ and $p < 0.0001$, respectively). Most surgeons (92%) use the sagittal balance as a factor for decision-making, and a small minority of those (42%) also think that patient outcomes will improve as a result of that (Table 3). The sagittal balance is considered decisive for the choice of surgical treatment for 89% of surgeons. The amount of experience using the sagittal balance concept in clinical practice does not significantly influence its role in decision-making.

Table 1. Baseline characteristics

Specialism	Orthopedic surgery	Neurosurgery	P value
Group size (%)	43/60 (72)	17/60 (28)	-
Experience in years (SD)	12.58 (10.85)	13.73 (9.11)	0.72
Q1: Thinks theory of sagittal balance is clinically relevant (%)	42 (98)	15 (88)	0.191
Q4: Applies sagittal balance in clinical practice (%)	36 (84)	5 (29)	<0.001
Q2: Orders X-ray of spine pre-op (%)	40 (93)	8 (47)	<0.001
Q3: Performs pre-op hip examination (%)	42 (98)	6 (35)	<0.001

Table 2. Theory of sagittal balance versus its clinical application

		Q4 Applies sagittal balance in clinical practice		P value
		Yes	No	
Q1	“Theory of sagittal balance is clinically relevant”	40	17	0.233
	“Sagittal balance is a hype”	1	2	
Q2: Always order X-ray of spine pre-op	Yes	38	10	<0.001
	No	3	9	
Q3: Always preforms hip examination pre-op	Yes	39	9	<0.001
	No	2	10	

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Table 3. Consequences of applying the sagittal balance concept in clinical practice

		Total (%)	Orthopedic surgeons (%)	Neurosurgeons (%)	P value
Q5: Consequences of applying sagittal balance	Choices in patient management depend on the sagittal balance	19 (52.8)	16	3	0.736
	Patient outcome have improved	2 (5.6)	2	0	
	Both patient management depend on the sagittal balance and patient outcome has improved	14 (38.9)	13 (41)	1 (25)	
	Sagittal balance does not affect patient management nor outcome	1 (2.8)	1 (3)	0	
Q6: Sagittal balance is used to decide for the right operative technique	Yes	32 (89)	29 (91)	3 (75)	0.39
	No	4 (11)	3 (9)	1 (25)	
Q7: A regression X-ray of the spine is ordered in case of aberrant sagittal balance	Yes	14 (39)	13 (41)	1 (25)	0.49
	No	22 (61)	19 (59)	3 (75)	

Discussion

This study was the first to investigate the current state of affairs regarding the acceptance and use of the sagittal balance concept in spine surgery by performing a survey among Dutch neurosurgeons and orthopedic spine surgeons. We found that an overwhelming majority (95%) of spine surgeons in the Netherlands, both neurosurgeons and orthopedic surgeons, consider the theory of sagittal balance enrichment for clinical practice. However, a far lower number of neurosurgeons (27%) apply the theory of the sagittal balance in their clinical practice compared to orthopedic surgeons (84%). Accordingly, neurosurgeons significantly perform fewer preoperative investigations that pertain to the sagittal balance parameters, namely the hip examination and conventional full-spine radiograms. Most neurosurgeons and orthopedic surgeons who use the sagittal balance concept in daily practice use it to guide their decision-making. Surprisingly, a much smaller percentage of those perceived that the introduction of the sagittal balance concept in clinical practice would lead to an improvement in patient outcomes.

The main challenge that was encountered in this study was the gap between widespread support for the theory of the sagittal balance concept and its clinical application, especially among neurosurgeons. There are no prior surveys concerning the practice of the sagittal balance concept for comparison and there are only a small number of surveys that compare neurosurgeons and orthopedic surgeons. Two surveys showed that orthopedic surgeons and neurosurgeons significantly differ in decision-making in spine surgery.[16,17] One survey taken in Korea showed significant differences regarding the management of various spinal disorders.[16] Significantly more orthopedic surgeons were in favor of aggressive discectomy versus fragmentectomy in the case of herniated disc surgery. Orthopedic surgeons were also significantly more often in favor of surgical intervention for traumatic spinal cord injuries. Lastly, more neurosurgeons were in favor of non-instrumented fusions, although this difference was not significant. The other survey was amongst spine surgeons in the United States of America and showed that orthopedic surgeons were significantly more likely to use instrumentation for degenerative lumbar spinal disorders.[17] Training could be the foundation of these differences in management and decision-making and it could also have its effect on differences in clinical application of the sagittal balance between neurosurgeons and orthopedic surgeons. A recent European study assessed the theoretical and practical skills of neurosurgeons and orthopedic surgeons who had or had not participated in a one-year spine fellowship.[18] There was no difference between orthopedic surgeons and neurosurgeons in terms of self-reported knowledge of the theory or practical skills. The spine fellowship did not significantly increase theoretical knowledge in most areas except for spinal deformity. This underlines that young European neurosurgeons and orthopedic surgeons have a thorough theoretical knowledge of spinal disorders, although knowledge about the sagittal balance was not specifically addressed. This might reflect the widespread support for the theory of the sagittal balance in our study. The practical skills competency did show significant differences between surgeons in favor of those who had participated in the fellowship. This could mean that more practical and hands-on training could lead to a more widespread clinical application of the sagittal balance concept in the Netherlands.

Most spine surgeons who apply the sagittal balance concept in clinical practice use it to guide their decision-making. Interestingly, a much smaller percentage thinks consideration of the sagittal balance has led to better surgical outcomes. Available literature regarding this topic is limited. No trials have been published today that compared surgical outcomes between patients who received correction of the sagittal balance versus no correction. Several authors have studied the relationship between radiologic and clinical outcome parameters and found that a correct sagittal balance leads to better clinical outcomes.[14,19,20] However, studies with higher levels of evidence would shed more light on the magnitude of absence or benefits of applying the sagittal balance. Compensation mechanisms, such as retroversion of the pelvis and hyperextension of the hip joints, have been studied and are found to have a significant influence on the sagittal alignment.[21,22] This suggests that a physical examination of the hips to diagnose hip osteoarthritis, which prevents the hips from hyperextension and the pelvis from tilting backward, cannot be ignored when applying the sagittal balance concept in daily practice and is essential to consider for every spine surgeon when a patient with LBP is evaluated.

We invited every practicing surgeon of the nationwide Dutch Spine Society to participate in this review, guaranteeing that all spine surgeons of the country had been invited. Furthermore, this survey had an excellent response rate (69%) compared to similar surveys amongst neurosurgeons and orthopedic surgeons,[18,23,24] including a recent Dutch survey with members of the DSS.[25] Moreover, since the questions in the survey had been tested by three spine surgeons and an epidemiologist before presentation to all spine surgeons, we assume that the questions were unambiguous and syntactically correct. This survey covered the most relevant aspects of spine surgery concerning the sagittal balance: the opinion about the theoretical value, its implementation in clinical practice, the frequency of preoperative diagnostics pertaining to the sagittal balance, the effect of the sagittal balance on decision-making and the perceived surgical outcome. Hence, we were able to give a complete overview of the current state of the sagittal balance in spine surgery in the Netherlands. Additionally, by securing anonymity and by approaching all spinal surgeons regardless of experience, region or training, we prevented bias. This survey was concise to discourage as few surgeons as possible from participating, but this also led to several shortcomings. We did not query the number of spine operations that each surgeon performs and whether there is a subset of patients for whom the sagittal balance is not taken into account. There might be differences between orthopedic surgeons and neurosurgeons in this respect, which could have been explanatory of the preoperative diagnostics of the sagittal balance. Neither was the distribution of indications for spine surgery nor the different spinal operative techniques to be used by the respondents in clinical practice investigated, which might also have explained differences between neurosurgeons and orthopedic surgeons. Additionally, although this survey questioned the experience of the surgeons, it did not take into account how large the subset was of surgeons who had undergone a spine fellowship or specific sagittal balance training. Knowledge of the differences in training background could have elucidated the differences between orthopedic surgeons and neurosurgeons.

Conclusion

In the Netherlands, the theory of the sagittal balance has widespread support, but it is not yet applied clinically by the majority of orthopedic surgeons and neurosurgeons. We expect the number of surgeons using the sagittal balance concept to increase with more training and continued presentation of evidence in its favor.

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II

SURGICAL TREATMENT OPTIONS

4

Surgical techniques in restoration lumbar lordosis: a biomechanical human cadaveric study

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Abstract

Introduction Degenerative changes of the lumbar spine lead in general to a decrease of lumbar lordosis (LL). This change affects the overall balance of the spine, and when surgery is deemed necessary, restoration of the LL is considered. How this restoration can be achieved is a matter of controversy. The main purpose of this cadaveric study was to investigate the different steps of common posterior surgical techniques to understand the contribution of each successive step in restoring LL.

Materials and methods Ten fresh-frozen human lumbar spine specimens were used to perform a sequential correction and instrumentation with a pedicle screw construct.

Results The mean LL angle measured at L3–L4 in intact condition was 12.9°; after screw insertion and compression, this increased to 13.8° (+ 7%, $p = 0.04$), after bilateral facetectomy to 16.3° (+ 20%, $p = 0.005$), after discectomy and insertion of interbody cage to 18.0° (+ 9%, $p = 0.012$), after resection of the lamina and the processes spinosus to 19.8° (+ 10%, $p = 0.017$), and after resection of the anterior longitudinal ligament to 25.4° (+ 22%, $p = 0.005$).

Conclusions Each step contributed statistically significantly to restoring segmental lordosis, with bilateral facetectomy contributing the most in percentage.

Introduction

Lumbar degenerative disorders, such as degenerative disc disease, degenerative spondylolisthesis and degenerative scoliosis can lead to anatomical changes and affect up to 60% of the aging adult population and is the most common cause of disability in patients between 45 and 65 years old.[1] Degeneration of the lumbar spine is characterized by osteophyte formation, reduced disc height and in some cases, spinal stenosis. A decrease of lumbar lordosis (LL) has been found with an increase in age.[2-6] This loss of LL affects the overall balance and, thereby, the biomechanics of the whole spine.[7] From L1 to sacrum, the contribution of the lordosis increases with every segment. Janik et al. stated that two-thirds of the total LL is located in the lower two levels (L4-L5 and L5-S1) and 85% is found in the L3-S1 segments.[8] The value of LL is highly variable in the general population and becomes even wider with increasing age, which may explain why some patients stay relatively asymptomatic while others complain about significant functional disability and pain.[9,10]

Optimal treatment remains controversial.[11-13] One of the most frequent indications for surgical management is neurologic symptoms. More relative indications are severe disability despite conservative treatment such as physical therapy and neurogenic claudication. A multicenter randomized controlled trial by Fritzell et al. showed better clinical outcomes for spinal fusion over non-surgical treatment.[14] However, comparative evidence demonstrating the superiority of one spinal fusion technique over another is lacking.[15] Posterolateral fusion (PLF) has been considered the golden standard surgical treatment for many years.[16,17] Although, with the increasing attention to the sagittal alignment of the spine over the last decades, lumbar interbody fusion (LIF) has increased in popularity due to the theoretical advantage of restoring the disc height and thus the LL.[18,19] Lumbar fusion in hypolordosis or even kyphosis is widely associated with adjacent segment degeneration.[20] According to several cadaveric studies, insufficient restoration of lordosis leads to degenerative changes in the adjacent segments, which has been confirmed in clinical studies as well.[21,22] Lazennec et al. showed post-fusion persistent pain to be significantly related to insufficiently restored LL, independent of other factors such as non-union.[23] Therefore, restoring the LL is considered to be one of the main goals of spinal fusion to improve clinical outcomes. Most studies comparing clinical outcomes of different surgical techniques focus on fusion rate rather than adequate lordosis restoration.[24] To quantify what surgical technique is most appropriate to restore lordosis, we investigated the different steps of the posterior approach in an experimental setup to understand the contribution of each successive step in restoring LL.

Materials and methods

Specimens and specimen preparation
Twenty-one freshly frozen (–20°) human cadavers (mean age: 79.2 years, range: 54 – 89) were screened for testing. The bodies were donated by last will in accordance with the national legislation. Body handling was done according to the guidelines of the Department of Anatomy of the University Medical Center Utrecht.
The specimens were evaluated with conventional radiograms of the lumbar spine. Eleven (52%) specimens with bridging osteophytes, collapsed intervertebral disc spaces or compression fractures were excluded, which resulted in ten specimens to be used for this study. The specimens were thawed 24 hours before testing and lumbar spinal segments (L1-L5) were harvested. Surrounding muscle tissue was carefully removed, keeping the anterior longitudinal ligament (ALL), facet joints and interspinous ligaments intact. The cranial and caudal vertebrae were potted in a casting mold and partially buried in a low melting point (48 °C) bismuth alloy (Cerrolow-147; 48.0% bismuth, 25.6% lead, 12.0% tin, 9.6% cadmium, and 4.0% indium). Adding screws into the vertebral body of the L1 and L5 vertebrae secured fixation into the alloy. All articulating parts were kept free. A three-dimensional system of coordinates was placed on the anterior side of the corpus of L2 to ensure a pure lateral radiogram.

Testing procedure
The test setup was described and validated previously.[25] Lumbar spines were placed horizontally in a custom-made 4-point bending device in which pure moments in flexion can be applied (Figure 1). Loads of 8 kg (785 N) were applied. After one minute of preloading, a radiogram was made. This setup obtains a physiological condition and guarantees that forces generate a moment that is equal at all levels of the lumbar spine. The spinal specimens were kept moist with 0.9% saline throughout the experiment. All tests were performed at room temperature.

At the start of the testing procedure, four pedicle screws were placed at level L3–L4. All steps were performed at this level. The sequence of successive steps was as follows:
1. Screw insertion and connection with roads
2. Bilateral facetectomy
3. Discectomy and cage insertion
4. Complete laminectomy and resection of spinous processes and interspinous ligaments
5. Resection of the ALL

Compression was given over the pedicle screws at the beginning and after each step by the same researcher. Pure lateral radiograms were obtained before testing and after each step (Figure 2).

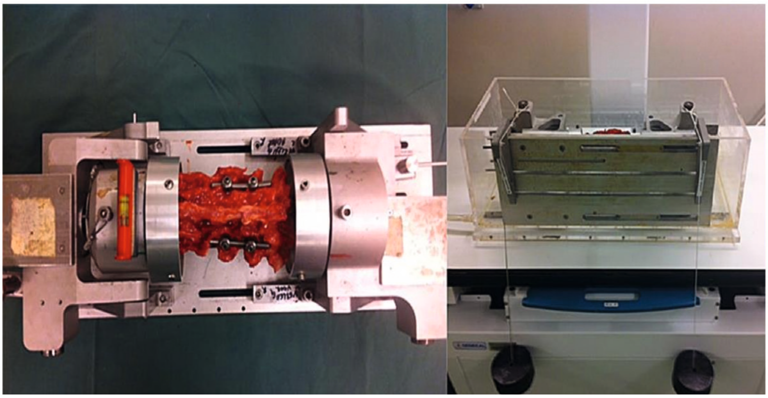

Figure 1.
The experimental setup is shown from above (left) and side (right) with lumbar spinal specimen (L1-L5) positioned in the four-point bending device and preloading weights.

Data analysis
Radiograms were uploaded to the Picture Archiving and Communication System (PACS). The first author measured the Cobbs angle between the superior endplate of L3 and the inferior endplate of L4 three times on consecutive days, using the measurements to calculate the mean absolute difference.

Statistical analysis
Statistical analyses were performed with Statistical Package for the Social Sciences software (SPSS 23.0, SPSS Inc., Chicago, IL, USA). First, data were tested for distribution by the Shapiro–Wilk test. Since data were not normally distributed, analysis was performed using the Wilcoxon signed-rank test. Intra-rater reliability was assessed using intra-class correlation (ICC) coefficients. Statistical significance was set at $p < 0.05$.

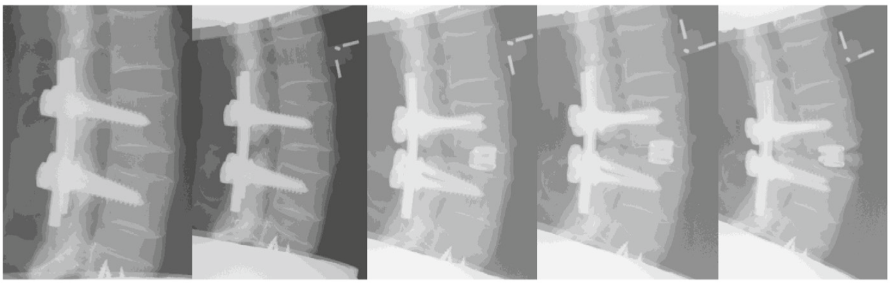

Figure 2. Lateral radiograms of successive steps of testing procedure.
From left to right: screw insertion, bilateral facetectomy, cage insertion, laminectomy and resection of ALL.

Table 1. Absolute measurements of Cobbs angle at L3-L4

	Intact	Screw insertion	Bilateral facetectomy	Cage	Laminectomy	Resection of ALL
Mean (°)	12.9	13.8	16.3	18.0	19.8	25.4
SD	3.5	3.9	4.5	5.0	4.6	5.1
Range (°)	7.1-16.9	7.2-21.0	10.0-25.3	10.8-28.8	11.2-28.8	13.9-27.0
%		7%	20%	9%	10%	22%
P value		0.04	0.005	0.012	0.017	0.005

Results

Each successive step resulted in a significant increase of the LL angle. The mean absolute measurements after each step are presented in Table 1. The ICC coefficients revealed an excellent intra-rater reliability (ICC = 0.91, $p = 0.001$).

Angle measurements

The mean LL angle in intact condition was 12.9°. After screw insertion and compression, the mean angle increased to 13.8° (+7%). Bilateral facetectomy resulted in a 3.4° (+20%) increase ($p = 0.005$). Discectomy and cage insertion resulted in a further increase of 1.7° (+9%, $p = 0.012$) compared to facetectomy and a total increase of 25% compared with the intact condition. After resection of lamina and processes spinous, the mean LL angle increased to 19.8° (+1.8°, 10%, $p = 0.017$) (+30% as compared with intact). The last step, resection of the ALL, resulted in the highest additional increase of 5.6° (+22%, $p = 0.005$) compared to the previous step. The total increase from the intact condition was 12.5° (+48%). Fold difference analysis is shown in Figure 3.

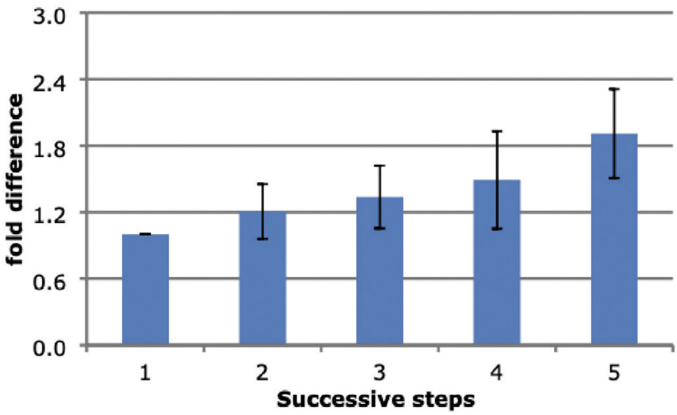

Figure 3. Fold difference analysis

Discussion

The surgical approach for lumbar fusion is an important determinant of achieving lordosis restoration. The traditional posterior lumbar interbody Fusion (PLIF) was first described by Cloward in the 1950s and enables a three-column fixation with 360° fusion and anterior support via a midline incision.[26] This approach includes a complete laminectomy to visualize and decompress nerve roots in case of neurological symptoms, but facet joints may only be undercut and not further destabilized. In 1982, Harms and Rolinger described the transforaminal lumbar interbody fusion (TLIF).[16] Neural injury and dural retraction are minimized by the lateral entry point. Originally, a unilateral facetectomy was performed during this surgical technique to insert the cage in the intervertebral disc. However, some spine surgeons remove the facet joints bilaterally.[27,28] In our study, we found a statistically significant increase in lordosis restoration after bilateral facetectomy. However, we did not compare unilateral with bilateral facetectomy. It has been reported by Tye et al. that there was no significant difference in segmental lordosis between unilateral and bilateral facetectomy.[29] Surprisingly, although no radiographic difference was found, only clinical outcome measurements in the bilateral cohort reached minimally clinical important difference (MCID), which was significantly greater than in the unilateral cohort. Other factors contributing to the improvement of clinical outcomes in bilateral resection of facet joints to explain this improvement could be reducing radicular pain by a complete foramina decompression or the phenomenon that the facet joints themselves cause the pain.[30] More recently, Snyder et al. found a statistically significant improvement of lordosis angle after complete bilateral facetectomy compared with unilateral facetectomy in seven cadaveric specimens, although this difference might not be clinically relevant as it was only 1.06°.[27] No previous studies have been found in the literature to compare our results of laminectomy contributing to the restoration of LL, as this is mainly performed to decompress nerve roots in patients with neurological deficits. However, laminectomy alone (without posterior fixation) is associated with a decrease of total LL during long-term follow-up and the rate of reoperation is higher compared with laminectomy with fixation.[31]

Our results showed a surprisingly small contribution of discectomy and cage insertion (+9%), although it was still statistically significant. We used the lordotic TLIF cage that best fitted the intervertebral space (11° in 2 specimens, 13° in 8 specimens) and placed it in the anterior third to the best as possible, so we hypothesized a greater contribution. This difference could be partly explained by an insufficient discectomy, which led to cage placement relatively posterior in three specimens. Therefore, we performed a subanalysis without these three specimens and found a mean increase of 4.8° (3.1° more than in the analysis with all ten specimens, $p=0.001$) compared with bilateral facetectomy only. In this analysis, laminectomy and cage insertion contribute significantly more to the total lordosis restoration (21%). These results underline not only the clinical relevance of introducing a cage to restore LL but

also the importance of placement in the anterior third of the intervertebral space. Furthermore, the correct placement of a cage offers a biomechanical advantage as well, as it is subject to a compressive load since the anterior column supports most of the body load. Combined with either an allograft or autogenous bone graft densely impacted within or next to the cage, bony fusion is stimulated.
This study showed a statistically significant increase of segmental lordosis at level L3–L4 after each step, with a total increase of 12.5° (49%) compared to the intact condition. The biggest contribution was found with resection of the ALL (+22%). This is consistent with prior studies, although the increase in our study was less. Uribe et al. demonstrated in a cadaveric study that sectioning the ALL and the use of a lordotic cage can provide an increase in segmental lordosis roughly equivalent to a Smith–Peterson osteotomy (up to 13.1° in a normal cadaveric spine).[18] The ALL is typically only sectioned during an anterior lumbar interbody fusion (ALIF) and is said to be most effective in the restoration of LL.[32] However, the anterior approach is associated with concerning complications such as retrograde ejaculation in males, ureter injury and major vessel injury to the blood or lymphatic circulation. It is mostly performed at levels L4-L5 and L5-S1.[33] Although, more recent literature shows good clinical results for lumbar fusion from L1 to S1.[34] Our results regarding resection of the ALL should be interpreted with care when comparing to results of ALIF in the literature as this was the last step after several posterior releases that have biased the outcome. Nevertheless, the increase of 5.7° after these posterior releases did show that the ALL was the restricting factor for a further increase in segmental lordosis restoration after bilateral facetectomy, cage insertion and laminectomy. This suggests that an ALL release from posterior could be an important last step of a PLIF procedure to restore the maximum amount of LL.

One of the limitations of our study is that we performed the different steps in the same order for each specimen and could therefore not correct for order effects. This may have overrated the effect of the last step but led to statistically significant results with a relatively small cohort. Another limitation is that we specifically selected specimens without any significant signs of degeneration to avoid biased results due to stiffness and facet joint hypertrophy. In the aging spine with disc degeneration and end plate changes, the results might be different.

In conclusion, the results presented here show an increase in segmental lordosis after each step performed during an instrumented PLIF procedure. Bilateral facetectomy was found to contribute the most in terms of percentage to restoration of LL of the posterior steps.

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Correction of the pelvic incidence using a bilateral extending pelvic osteotomy: a proof of concept study

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Abstract

Introduction The aim of this proof of concept human cadaver study was to quantify the effect of a bilateral extending pelvic osteotomy (BEPO) on pelvic incidence (PI) as a potential alternative for a pedicle subtraction osteotomy (PSO) in patients with severe sagittal spinal malalignment.

Materials and methods Ten fresh-frozen human cadavers were treated with the BEPO technique. CT images were made before and after the osteotomy and pure sagittal images were created on which PI was measured.

Results The mean pre-osteotomy PI was 47.9° (range 36.4 – 63.9) and the mean post-osteotomy PI was 36.5° (range 22.1 – 54.4). The mean correction was −10.4° with a range of −8.4° to −17.3° ($p = 0.03$), which resulted in a mean decrease of 23% in the PI (range 16 – 42).

Conclusions There was a feasible and effective correction of PI using the BEPO technique on the ilium. This was a preliminary cadaveric study. No conclusions could be made on global sagittal alignment. We postulate that an extending osteotomy of the ilium could be a potential alternative for a PSO, reducing the complexity of spine surgery in patients with severe sagittal spinal malalignment.

Introduction

The pelvis is the pedestal for spinal alignment. The recognition of pelvic morphology as a regulator of global sagittal spinal alignment and determinant of spinal pathology is increasing.[1-3] As humans evolved towards bipedal posture, morphological changes of the pelvis were crucial. A fully erect bipedal posture with extended hips and knees without an adaptation of the pelvis would require an extreme lumbar lordosis (LL) to keep the trunk above the femoral heads.[4] Lordotic angulation between the ischium and ilium, quantified as the ischio-iliac angle (IIA), allowed humans to stand upright with a relatively small LL.[5] The IIA is strongly related to the PI, a morphological 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).[2,5] Both parameters are unique to each individual and stay constant after adolescence under normal circumstances. The sacral plate is the base of the spinal column; thus, its position influences the degree of LL to maintain a balanced upright position. Low PI is associated with decreased LL and high PI with increased lordosis.[6] Schwab et al. formulated this as LL = PI±9.[7]

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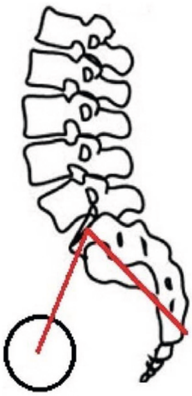

Figure 1.
Pelvic incidence (PI): the angle between the line perpendicular to the sacral plate at its midpoint and the line connecting this point to the axis of the femoral heads.

Many disorders of the spinal column can lead to changes in this equilibrium. Because PI remains relatively constant during life, loss of LL may lead to a mismatch between PI and LL and increased pelvic tilt (PT). This loss of sagittal alignment is associated with reduced quality of life, especially increased PT.[8-10] In patients with a limited PI-LL mismatch, surgical correction can be achieved by restoring disc height with a variety of interbody surgical techniques. In case of severe loss of LL, restoration can only be achieved by a comprehensive correction osteotomy such as multiple Smith-Petersen, Ponte- or pedicle subtraction osteotomies (PSO), according to the

SRS-Schwab Radiologic Classification.[11] These procedures, however, are associated with many complications, such as blood loss, deep wound infection and neurological deficits, especially in patients with previous lumbar spinal surgery.[12]
An alternative place for an osteotomy could be between the sacral plate and the femoral heads to decrease PI. Based on the correlation between PI and the IIA, we hypothesize that correction of these parameters may reduce the need for more drastic osteotomies in the lumbar spine. Similar pelvic osteotomies such as Salter[13] and Chiari[14] have been well described for the treatment of hip dysplasia. However, these are performed in young children and are mostly performed on one side. The effects of a bilateral osteotomy on the restoration of sagittal spinal malalignment have received little attention thus far.[15,16] The aim of this study is therefore to quantify the anatomical effects of bilateral anterior open-wedge correction osteotomies of the ilium (further referred to as bilateral extending pelvic osteotomy [BEPO]) on PI in human cadavers.

Materials and methods

Specimen preparation
We included 10 human cadavers (mean age 74.3 years, range 54 – 92) in this study. In accordance with Dutch legislation, the bodies were donated and destined for medical education and research to the Department of Anatomy of the University Medical Center Utrecht by last will. Body handling was done according to the guidelines of the Department of Anatomy. None of the deceased subjects had any history of pelvic or hip surgery. The freshly frozen (−20°) cadavers were thawed 24 hours before the pelvis and sacrum were harvested. The pelvic soft tissues were carefully removed to improve the visibility of the bone, especially fractures or fissures, and prevent soft tissue obstructing the most ideal correction. No ligaments were removed. Computer tomography (CT) scans were obtained before and after the BEPO procedure (iCT, 120 kV, slices 0.9 mm, Philips, Eindhoven, The Netherlands).

BEPO surgical technique
Each pelvis was positioned supine. With a thin oscillating saw blade, a straight cut was made starting from the area between the anterior-superior and anterior-inferior iliac spine and targeting the greater sciatic notch. The same cut was performed on the contralateral side. In the first five specimens, the saw cut ended at the arcuate line of the ilium, approximately two-thirds of the length between the iliac crest and the sciatic notch. For specimens 6 to 10, the surgical technique was improved by making the saw cut past the arcuate line (approximately 80% of the length between the iliac crest and sciatic notch) to prevent a potential fracture during osteotomy distraction. The thin blade osteotome was gently placed in the osteotomy gap to measure the angle when the tip of the instrument reached as close to the hinge point as possible. The insertion depth corresponded with the previously sawn cut. A second

blade osteotome was then slowly inserted to the same depth. A third blade was then inserted between the previously inserted blades. Then, a TomoFix Bone spreader with an 8 mm blade (range 6 – 20°) was inserted and a hexagonal screwdriver was used to open the spreader to the desired 15° level. This technique is based on the medial open-wedge tibial osteotomy described for the TomoFix plate.[17] This first osteotomy was kept open with bone spreader forceps. The same procedure was then performed on the contralateral side. Next, two TomoFix bone distractors (Johnson and Johnson Services Inc., New Brunswick, NJ, USA) were carefully hammered into both osteotomies until the hinge was reached. The screws of the TomoFix were slowly turned with a screwdriver to gently spread the osteotomy to the desired opening angle of 15°. To maintain the wedge, a PLIF cage size 15 (EIT Emerging Implant Technologies Inc., Tuttlingen, Germany) was inserted (Figure 2).

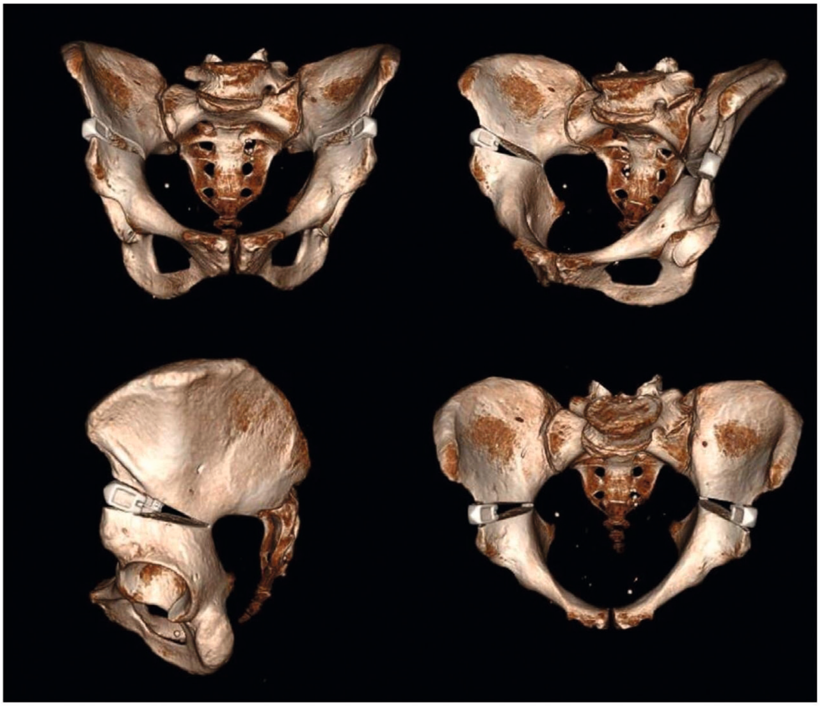

Figure 2. 3D reconstruction of CT scan: AP, ¾, lateral and proximal view

Data and statistical analysis

CT images were uploaded to the Picture Archiving and Communication System (PACS) of the University Medical Center Utrecht (ChipSoft Inc., Amsterdam, The Netherlands). With multiplanar reconstruction (MPR), pure sagittal reconstructions were created, with both acetabular bones projected exactly overlying each other.

These reconstructed images were imported into the previously validated software Surgimap® (Nemaris Inc., New York, NY, USA). The specialized sagittal alignment tool was used to measure PI, where acetabulum and the superior endplate of S1 were identified, after which the software automatically generated PI. Each image was measured four times (three times by the first author on three consecutive days and once by one other observer). Measurements were used to calculate the mean absolute difference.
Statistical analyses were performed with Statistical Package for the Social Sciences software (SPSS 23.0, SPSS Inc., Chicago, IL, USA) using the Wilcoxon signed-rank test and Mann–Whitney U test. Inter-rater and intra-rater reliability was assessed using intra-class correlation (ICC) coefficients. Statistical significance was set at $p < 0.05$.

Results

An overview of the demographics of the specimen and the results of the osteotomy on PI are presented in Table 1. We found BEPO to be considerably effective in changing PI. The mean pre-osteotomy PI was 47.9° (range 36.4 – 63.9) and the mean post-osteotomy PI was 36.5° (range 22.1 – 54.4). The mean correction was −10.4° with a range of −8.4° to −17.3° ($p = 0.03$), which resulted in a mean decrease of 23% (range 16–42). Both inter- and intra-reliability analyses revealed excellent agreement for PI measurements (ICC = 0.92, $p = 0.004$ resp. ICC = 0.97, $p = 0.001$).
A subanalysis was performed on specimens 1–5 (group A) and specimens 6–10 (group B) because of the slight adjustment in the surgical technique. The mean correction in group A was −10.2° ($p = 0.04$) and in group B −12.7° ($p = 0.04$). When comparing both groups, no statistically significant difference was found ($p = 0.46$).

Table 1. Overview of specimen and effect of BEPO on PI

Specimen	Sex	Age (y)	Preoperative PI	Postoperative PI	Correction (%)	
1	Female	85	37.5	28.6	-8.9 (24)	
2	Female	68	59.4	49.8	-9.6 (16)	
3	Female	89	36.4	27.6	-8.8 (24)	
4	Male	54	50.5	35.4	-15.1 (30)	
5	Male	58	43.9	35.5	-8.4 (20)	
6	Female	70	39.4	22.1	-17.3 (42)	
7	Male	75	63.1	47.5	-15.6 (25)	
8	Male	92	44.1	34.1	-10.0 (23)	
9	Female	83	63.9	54.4	-9.9 (16)	
10	Female	69	41.3	30,1	-11.2 (27)	
Mean		74.3	47.9	36.5	-10.4 (23)	p = 0.03

Technical complications

In specimens no. 1 and no. 3, a small unilateral hairline fracture occurred when the opening wedge was created with the bone distractor. However, these fractures did not cause any dislocation and the stability was not reduced. Thus, the clinical relevance has yet to be established.

In specimen no. 4, a unilateral fracture occurred that did have an impact on the stability and would have needed additional fixation (osteosynthesis) in a setting. After refinement of the surgical technique, no further fractures were observed when the saw cut was made beyond the arcuate line.

Discussion

The increased recognition of the importance of sagittal spinopelvic alignment has led to the consideration that the pelvis could be seen as pelvic vertebra, as suggested before by Dubousset.[18] Spinopelvic parameters, such as IIA, PI and LL are strongly correlated with each other.[19] These patterns are essential in understanding the differences in biomechanical loading of the spine and etiology of spinal pathologies such as degenerative disc disease and spondylolisthesis and the influence on sagittal spinal malalignment and its surgical treatment.

In the present study, we quantified the effect of a BEPO on PI in human cadavers. We found a statistically significant decrease of PI to prove the concept. The effect on the global sagittal alignment and the clinical relevance has yet to be established. We speculate that this may diminish the need for complex PSO surgeries with concurrent complications and increase the need for less complex procedures such as SPO or the use of hyperlordotic cages instead since a smaller PI-LL mismatch needs to be addressed. This can only be done by conducting the BEPO procedure on alive patients.

An economical standing equilibrium in bipedal posture is influenced by many parameters, as described by Duval-Beaupere et al. In the clinical setting, PI is a more practical parameter than the IIA, as PI can be measured on lateral radiographs.[3] Besides PI as a constant anatomical parameter, sacral slope (SS) and PT play an important role in analyzing sagittal spinal alignment (Figure 3).[20] These parameters are influenced by the position of the pelvis in space and could therefore not be assessed on the supine CT images in this study. Mathematically, PI, PT and SS can be linked by the formula: PI = PT + SS.[2] In patients with fixed flat back syndrome, a decrease of PI could reduce or completely nullify the PI-LL mismatch (PI-LL > 10) which might have a positive effect on the health-related quality of life (HRQOL). Even more, due to the anatomical relation, we consider any decrease of PI in patients with fixed LL may lead to a decrease of PT, which improves the HRQOL as well.[10,20] Surgical correction of PI-LL mismatch has also been associated with spontaneous improvement in knee flexion as a compensation mechanism.[21]

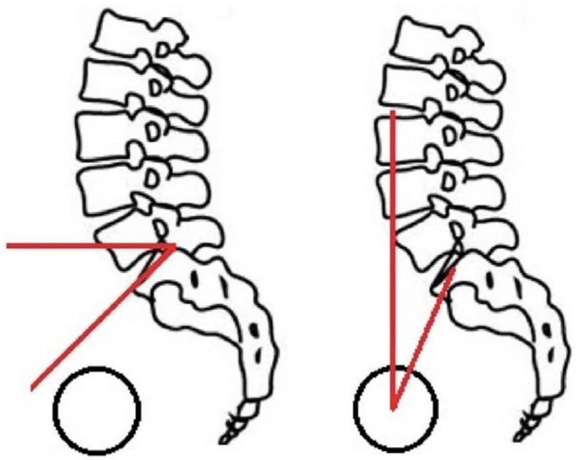

Figure 3.
Left: sacral slope (SS): the angle between the superior endplate of S1 and a horizontal line. Right: pelvic tilt (PT): the angle between the line connecting the center of the superior endplate of S1 and the center of the femoral heads and a vertical line.

In case a complex lumbar correction osteotomy such as a PSO is less appealing due to its known high risk of complications,[22] previous spinal surgery patients with severe sagittal malalignment could be eligible for this osteotomy. Clearly, the effects on the restoration of global sagittal spinal malalignment and HRQOL have to be confirmed by a prospective clinical series. However, simulation of the effect of BEPO on the sagittal vertical axis (SVA), defined as the distance between the C7 plumb line and the posterosuperior corner of S1 in the sagittal plane, in Surgimap® (Nemaris Inc., New York, NY, USA) found a promising decrease of 73.21 mm (48%) with an osteotomy angle of 10° (Figure 4). Even more, this simulation was not able to correct for flexion of the knees, so the actual effect on the correction of the sagittal malalignment and its concurrent compensatory mechanisms may even be more extensive.

Technically, a bilateral osteotomy is not more demanding than a unilateral procedure. When the osteotomy is bilateral, the geometrical relation between the sacrum and femoral heads is modified with a decrease of PI as a consequence. CT simulation by Bodin et al. suggested that PI correction varies following a mathematical law: PI end = PI initial— *a* x (osteotomy angle). For the Salter osteotomy, the value of *a* was 0.4964 and for the modified Salter osteotomy *a* was 0.3725, which was verified on a cadaveric model.[16] Using this formula to predict the PI decrease, using our osteotomy angle of 15°, we would, according to this formula, lead to a PI decrease of 0.4964 × 15 = 7.446° for the Salter and 0.3725 × 15 = 5.5875° for the modified Salter osteotomy. We found a substantially larger correction, however, which might be explained by the specific modifications in the BEPO procedure. Our surgical technique is a modification of the original Salter osteotomy, with the most important modification being that the open wedge was created with a saw cut through the arcuate line of the ilium, leaving a stable posterior cortex to act as a hinge. Also, Salter tested the pelvis by separating the halves in the mid-sagittal plane and fixing them on a rigid board to compare different osteotomies in the same specimen. We tested with the whole pelvis in the supine position. To our knowledge, Bodin et al. are the only other authors who have investigated the effect of an osteotomy of the ilium on PI in cadavers before. They focused on comparing different techniques rather than quantifying the impact of the osteotomy on PI. They also presented a small clinical series of patients who underwent bilateral (n=8, of which one with additional psoas tenotomies) or unilateral (n=3, of which one with contralateral closure and one with contralateral Chiari osteotomy) Salter innominate osteotomy. After a mean follow-up of 9.27 years (range 3 – 19 years), the mean PI reduction was 17° which, as an absolute number, is far more than in our results. The mean preoperative PI of 74.6° in their study was relatively high. With a relative decrease of 23%, this is comparable to our data. SVA decreased from 97.2 mm to 50.2 mm (−48.4%), which is almost within normal value (< 50 mm) and similar to our simulation. Patients had to use crutches for 6 weeks, wear a hemi-spica cast for 3 months and a lumbar orthosis for an additional 3 months. Nevertheless, many complications were reported, including persisting pain complaints (n=10), hip disorders leading to total hip replacement (n=3) and femoral neuropraxia (n=1). In our cadaveric study, the osteotomy was complicated by a fracture with dislocation in specimen no. 4. We argue that the cut did not have the appropriate length, which increased the local stress on the posterior cortex during the bone distraction and resulted in the fracture which would have needed additional fixation for stability in the clinical setting. We then adjusted the surgical technique as described. In the subanalysis, we found a statistically significant decrease in both separate groups after adjusting the technique. The different groups did not differ in their effect on the correction of PI. Following this adjustment, no fissures or fractures occurred with the same osteotomy angle. In a clinical setting, preoperative measurement of the total length of the ilium on CT scans would enable planning of the desirable saw length preoperatively and reduce the risk of such a complication. We decided not to exclude this specimen to prevent selection bias.

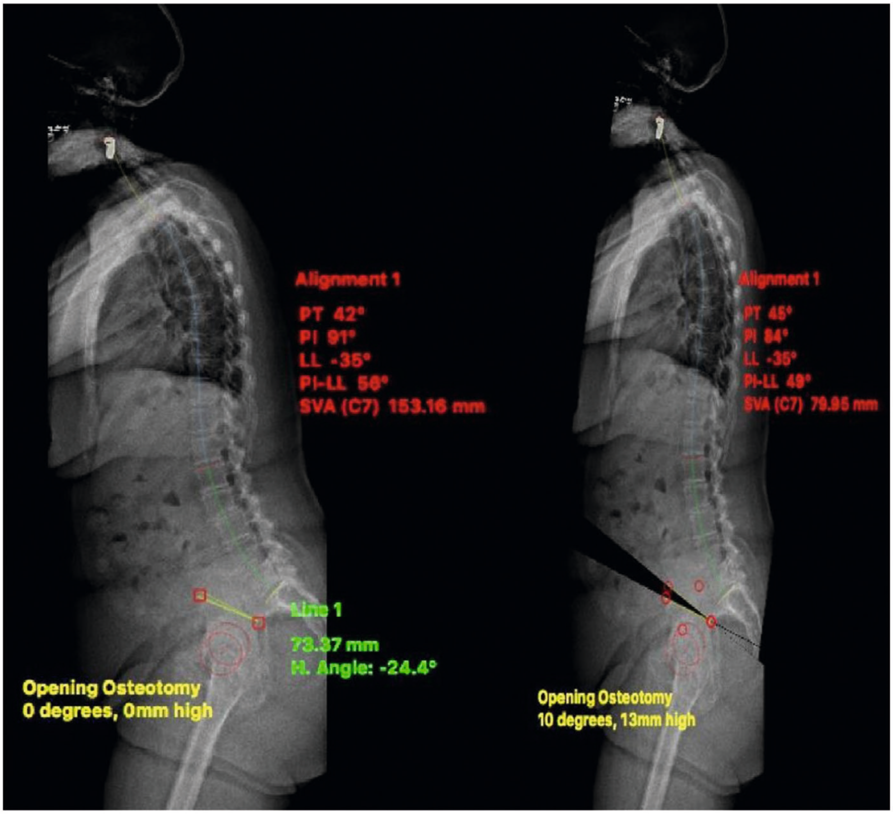

Figure 4. Simulation of effect on the sagittal vertical axis (SVA) after a bilateral extending pelvic osteotomy with an osteotomy angle of 15°.
Pre-osteotomy (left): PI 91°, SVA 153.16mm. Post-osteotomy (right): PI 84°, SVA 79,95 mm.

Limitations
The most important limitation of this study is that it is a cadaveric study. Therefore, no conclusions could be made on global sagittal alignment nor the effect on soft tissues and muscles or concurrent postoperative pain. Also, we used a PLIF cage and no fixation plate in this study because the primary goal was to maintain the opening of the created wedge. In a clinical trial, a specifically designed cage that fits the patient-specific wedge perfectly with a fixation plate to provide pelvic stability should be used. A clinical trial will have to establish the effects and the clinical relevance. Because the study was set up as a proof of concept study, testing ten cadavers was enough to answer the main question and find a statistically significant difference in PI.

Future clinical implications
The clinical feasibility and relevance have yet to be established in a clinical trial. Although, the technical aspect of the surgery was found to be feasible in this cadaveric

study. One of the main concerns for clinical implications is the risk of pseudoarthrosis. In a clinical trial, these patients should be preoperatively tested for osteoporosis. Also, a specifically designed cage should be used to improve bone ingrowth with a fixation plate to provide pelvic stability. This should be stable enough for patients to be able to mobilize with two crutches from the day after the surgery to 5–6 weeks after.

We speculate that this BEPO procedure may diminish the need for complex PSO surgeries with concurrent complications and increase the need for less complex procedures such as SPO or the use of hyperlordotic cages instead since a smaller PI-LL mismatch may need to be addressed. We do not believe BEPO will be a full alternative to complex spine surgeries but instead be considered as an extra tool in the armamentarium of the spine surgeon which may significantly reduce the extent of the spinal procedures in severely malaligned patients.

In conclusion, the correction of PI after a BEPO observed in this study was feasible and effective. We postulate that a BEPO could be an eligible tool to reduce the complexity of spinal procedures in patients with severe sagittal spinal malalignment. A prospective clinical series is required to further investigate the effects and safety in patients.

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6

Pelvic osteotomies for correction of sagittal imbalance of the spine: an in-silico study comparing four different osteotomies

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Abstract

Introduction Three-column spinal osteotomies are common to restore sagittal balance. However, these procedures are challenging. Pelvic osteotomies may be a feasible alternative, although instability and compromised correction are concerning, which dome-shaped osteotomies may mitigate. As a possible and novel alternative for spinal osteotomies, pelvic dome and open wedge osteotomies for correction of sagittal spine balance were compared.

Materials and methods Four in-silico pelvic osteotomies were performed on 3D CT-reconstructions: bilateral extending pelvic osteotomy (BEPO) and dome pelvic osteotomies (DPOs) around the center of the sacral endplate (SE-DPO), sacroiliac joints (SI-DPO) and centers of the acetabula (A-DPO).

Results We measured pelvic extension and bone contact surface (BCS) after 10°, 15° and 20° extension and the length of the sacropelvic ligaments after 20° extension. In radiographs of five samples of failed back surgery, we measured the effect on the sagittal vertical axis (SVA) and the T1 pelvic angle (TPA). Pelvic extension was similar for all types of osteotomy. After 20° extension, BCS was 34.1% (SE-DPO), 28.2% (SI-DPO) and 30.6% (A-DPO). The average shortening of the spinopelvic ligaments was 2.3% after the BEPO, 22.0% after SE-SPO, 17.0% after SI-DPO and 11.8% after A-DPO. After 15° correction, SVA correction was 12.6cm and TPA correction was 5.8° after BEPO. After SE-DPO, the correction was 14.5cm and 14.1°; after SI-DPO 13.4cm and 13.0° and after A-DPO 12.6cm and 0.0°.

Conclusions A-DPO appeared to be the most predictable and reliable pelvic osteotomy. However, this is technically demanding and shortens the pelvic floor ligaments. BEPO is less demanding with minimal effect on the ligaments, however, it requires more complex stabilization methods. Feasibility and safety tests are required as the next step.

Introduction

The evolution of humans to a bipedal posture has led to significant morphological changes in the spine and pelvis.[1,2] Among these changes is the development of an additional posterior concavity of wedged lumbar intervertebral discs and vertebrae, referred to as lumbar lordosis (LL).[3] A substantial reduction in LL, often due to lumbar degenerative disc disease, can cause sagittal malalignment and low back pain in these patients. This condition is a major global health issue, ranking as one of the top five causes of years lived with a disability.[4] The sacrum's orientation significantly determines sagittal spinal alignment. This relationship is largely influenced by the pelvic incidence (PI), a patient-specific pelvic morphology parameter that describes the sacrums orientation within the pelvic ring (Figure 1). As the sagittal pelvic morphology is more-or-less fixed, the pelvic orientation in relation to the femoral heads directly influences the takeoff of L5 and therefore the LL.

Over a decade ago, Dubousset first proposed the concept of the *cone of economy* and emphasized the importance of sagittal rotations of the 'pelvic vertebra' to maintain global body balance.[5] Subsequently, Schwab et al. identified that an excessive mismatch between the PI and LL, particularly when LL<PI±9°, is more likely related to mechanical complications after spinal fusion.[6] This PI-LL mismatch has gained increasing recognition as a crucial factor in sagittal spinal (re)alignment.[7-9] Compensatory mechanisms, such as posterior pelvic tilt (PT) and knee flexion, are used to maintain the trunk's alignment straight over the hips and feet. However, these adaptations are physically demanding and often associated with reduced quality of life.[10,11] Severe, rigid sagittal spinal deformity often necessitates extensive spinal osteotomies to realign the spine and balance the head above the pelvis. These procedures carry a significant risk for complication, which includes neurological deficits and material failure.[12,13] In cases where initial osteotomies were unsuccessful, revision surgeries pose an even greater risk of complications.[14]
The lower the level of the extension osteotomy, the larger the effect on global spinal alignment due to its proximity to the rotation point of the PI. Therefore, an extension osteotomy in the 'pelvic vertebra' with a bilateral extending pelvic osteotomy (BEPO) of the iliac bone seems a logical step. This method's viability has been supported by case series[15] and laboratory research.[16] However, BEPO presents substantial risks, including posterior hinge fractures leading to pelvic instability and subsequently a compromised PI correction. To address the challenge of stability and secondary translation of wedge osteotomies in the non-axial skeleton, dome-shaped osteotomies are a well-known strategy. They may offer more predictable, manageable corrections and stable bone-to-bone fixation due to maintained contact surfaces. Therefore, this study aims to do a first investigation of several pelvic dome osteotomies and compare these to the open wedge osteotomy in an in-silico model study. This research focuses on the potential pelvic extension measured by a novel

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parameter developed for this purpose: the pubic sacral angle (PSA) (Figure 1), bone contact surface area, the effect on the length of the sacropelvic ligaments and global sagittal balance, comparing pelvic dome type and open wedge osteotomies as an alternative for spinal osteotomies.

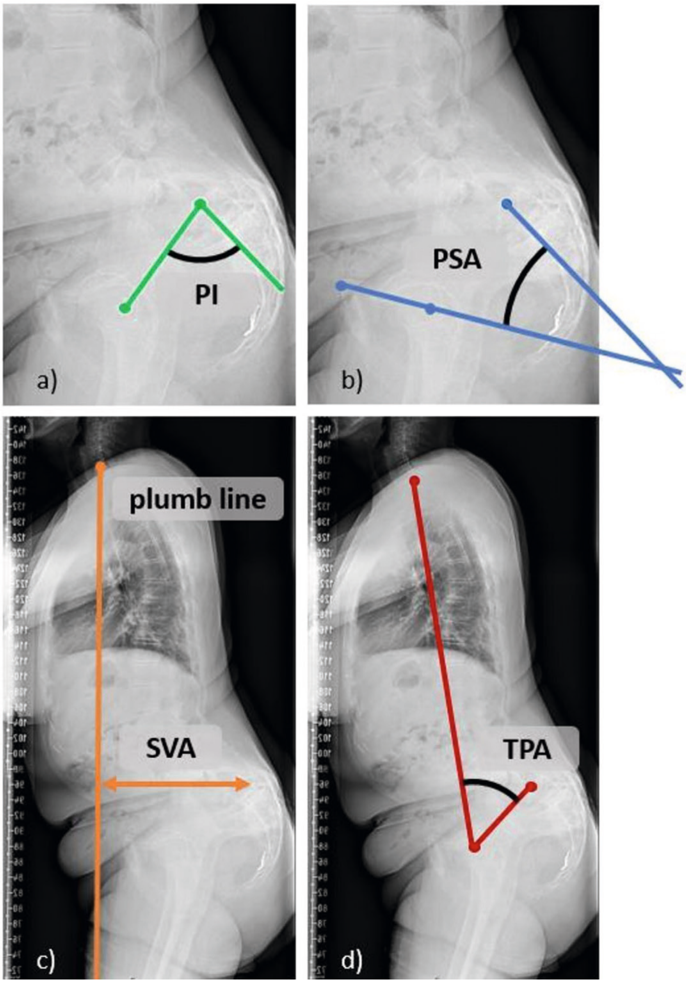

Figure 1.
a) Pelvic incidence (PI): the angle between the line perpendicular to the sacral plate at its midpoint and the line connecting this point to the center of the axis of the femoral heads.
b) Pubic sacral angle (PSA): the angle between the line through the pubic tubercule and the center of the acetabulum and the line perpendicular to the sacral endplate at its midpoint.
c) Sacral vertical axis (SVA): the distance between the plumb line from the center of the vertebral body of C7 and the posterosuperior corner of the sacral plate.
d) Th1 pelvic angle (TPA): the angle between the line connecting the center of the vertebral body of Th1 to the femoral heads and the line connecting the femoral heads to the center of the sacral plate.

Materials and Methods

Data selection

Ten computed tomography (CT) scans from a pre-existing clinical database were selected. Gender distribution was equal, with an average age of 27 years (ranging from 21 to 35). Each CT scan comprehensively included the entire pelvis and had a slice thickness of 0.9mm. Exclusion criteria were a history of pelvic or hip fractures or any related surgeries. In addition, five standing full spine radiographs, including the pelvis of failed back surgery patients with a sagittal vertical axis (SVA) >10cm, were selected from an orthopedic clinical database. The average age was 71 years (range 66 to 77 years). The study was conducted under the protocol number 16-612/C. The medical ethical committee judged the study not to be subject to the Medical Research Involving Human Subjects Act.

Three-dimensional (3D) bone model generation

Segmentation of the pelvis and femora was done with Mimics (version 24.0, Materialise, Leuven, Belgium) using bone thresholding. 3D reconstructions were exported to STL files and transferred to 3-Matic (version 16.0, Materialise, Leuven, Belgium) to perform the in-silico analysis.

Pelvic coordinate system

To ensure reproducibility and generalizability for all osteotomies, the Anterior Pelvic Plane (APP) coordinate system was utilized.[17] For the coronal plane, the right and left anterior superior iliac spine (ASIS) and the midpoint of the pubic tubercles (MPT) were used. The sagittal plane was defined through the MPT and perpendicular to the coronal plane.[17,18]

Osteotomy simulation (Figure 2)

Three different variants of a dome pelvic osteotomy (DPO) were developed and performed in-silico on each of the ten 3D reconstructed pelvises. Similarly, the BEPO was performed and all osteotomies were compared regarding pelvic extension, bone contact surface area and length of spinopelvic ligaments.

The four simulated osteotomy techniques are described as follows:

- The BEPO is a straight anterior open-wedge osteotomy. It starts just below the ASIS, extends above the acetabular roof and ends just past the arcuate line 10mm anterior to the greater sciatic notch. This dorsal endpoint was used as the hinge position.[16]
- Three different rotation centers were used for the simulated DPO techniques:
    - o the coronal axis halfway the sacral endplate (SE-DPO)
    - o the sacroiliac joints (SI-DPO)
    - o the axis connecting the two acetabular centers (A-DPO)

Virtual cylinders were constructed along these points with axes aligned parallel to the APP x-axis. The cylinder diameters were adjusted considering anatomical boundaries related to the type of osteotomy and the size of the pelvis. All four osteotomies were considered in the context of the pelvis' natural rotation over the hip axis, which is regarded as the physiological spinopelvic axis. The accessibility of the osteotomy sites was confirmed by experienced orthopedic surgeons considering critical structures such as the vasculature, nerves and essential muscle attachments. Three magnitudes of extension; 10°, 15° and 20° were simulated.

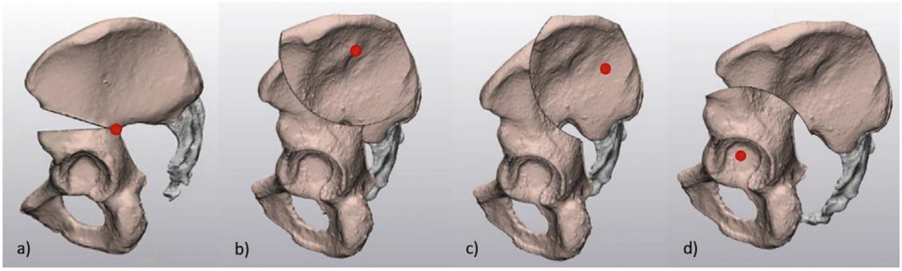

Figure 2.
a) bilateral extending pelvic osteotomy (BEPO), dome pelvic osteotomy (DPO) around b) the coronal axis halfway the sacral endplate (SE-DPO), c) the sacroiliac joints (SI-DPO) and d) the axis connecting the two acetabular centers (A-DPO). The points of rotation are indicated in red.

Two-dimensional (2D) osteotomy simulation

The 2D osteotomy simulation was achieved by deploying a customized script to automatically load and cut the standing full spine radiographs using Python (version 3.7, Python Software Foundation). The validation of the script was executed by performing a manual osteotomy on two radiographs. The ASIS, sciatic notch, the center of the C7 vertebrae and the centers of the sacral endplate, sacroiliac joints and two acetabula were selected as landmarks. Subsequently, the radius of the SE-DPO, SI-DPO and A-DPO were determined. Next, the radiographs were cut along the determined osteotomy (BEPO) and domes (DPOs). The cranial part of the image was extended 15° after each of the osteotomies.

Outcome measures

To evaluate the effectiveness of the four osteotomy techniques, four outcome measures were assessed:

1. Effect on pelvic extension: the PI was inadequate as a measure for sagittal morphology changes after a pelvic osteotomy, as only one point (and not a line) is defined below the osteotomy. The pubic sacral angle (PSA) was developed and used in this study, which is defined by the angle between two lines: one line cranial (sacral plate) and one caudal to the planned pelvic osteotomies (Figure 1).

2. Assessment of bone contact surface area: the DPOs rely on a substantial bone contact surface between the cranial and caudal parts. The bone contact after 10°, 15° and 20° rotation was measured in 3Matic software. The relative contact area was calculated using the following formula: bone contact surface percentage = bone contact surface of ilium parts (mm^2) / bone surface at osteotomy surface (mm^2).[18] To determine whether there is a linear relationship between the percentage of bone contact and the angle of rotation, we employed the least squares method (LSM), creating the most accurate line of fit. This produces a regression line that is closest to the data points in terms of vertical distance. For each type of DPO, a regression line was created that best fits the mean bone contact percentages at 0°, 10°, 15°, and 20° rotations. The quality of these fits was evaluated using the coefficient of determination: R2, where a value of 1.0 signifies an exact fit. An R2 value lower than 0.5 suggests a weak correlation between the bone contact percentage and the rotation angle.
3. Sacropelvic Ligament Length (Figure 3): both the sacrospinous (SSL) and the sacrotuberous (STL) ligaments are integral to the overall stability of the pelvis and functionality of the pelvic floor. The change in length of both ligaments was measured at 20° extension.
4. Effect on sagittal balance: the SVA and the Th1 pelvic angle (TPA) (Figure 1) were measured on calibrated standing full spine radiographs before and after the four osteotomies with 15° extension.[19]

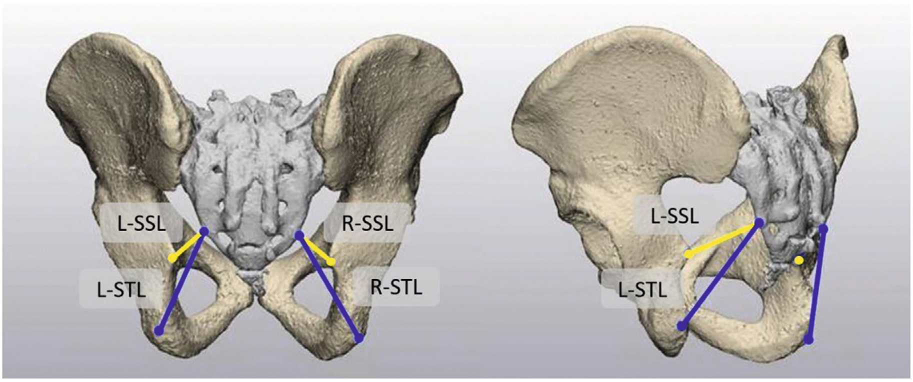

Figure 3.
Measurements of the left and right sacrospinous ligament (L-SSL and R-SSL): from the most medial point on the ischial spine to the center of the lower posterior sacral foramen. Measurements of the left and right sacrotuberous ligaments (L-STL and R-STL): from the same sacral origin as the SSL to the midpoint of the ischial tuberosity.

Statistical analysis
Measurements are shown as mean ± standard deviation (SD). 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 normally distributed based on 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 (Table 1)

Effect on pelvic extension
The mean change of PSA after 10°, 15° and 20° was similar to the amount of given corrective rotation and osteotomy angle for all four osteotomies.

Bone contact surface (Figure 4)
After a rotation of 20°, the bone contact was 34% ± 8,87 after the SE-DPO, 28.2% ± 10.04 after the SI-DPO and 30.6% ± 4.73 after the A-DPO. Each LSM fit had an R2 larger than 0.99. This implies a linear correlation between the PSA and the bone contact.

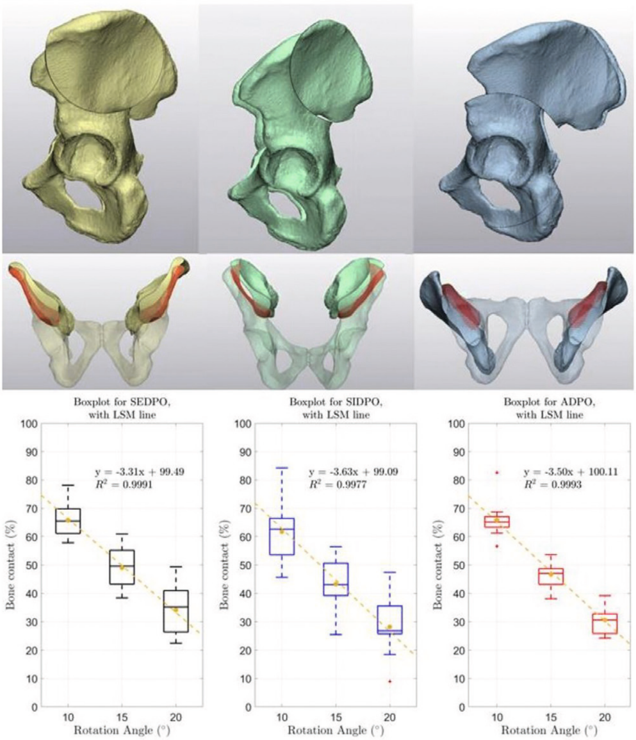

Figure 4.
Sagittal and caudal view of the SE-DPO, SI-DPO and A-DPO after 20° rotation and boxplot of the least squares method after 10°, 15° and 20° rotation. The bone contact between the ilium parts is visualized in striped red.

Length of spinopelvic ligaments

For the SSL, shortening at 20° extension was 2.3mm (2.7%) after the BEPO, 23.6mm (27.4%) after the SE-DPO, 18.5mm (23.5%) after the SI-DPO and 7.4mm (6.5%) after the A-DPO. For the STL, the shortening at 20° extension was respectively 2.4mm (1.8%), 22.4mm (17.5%), 15.5 (12.1%) and 16.3mm (12.3%). The average shortening after the BEPO was 2.3mm (2.2%). For the dome osteotomies, this was considerably larger: 23.0mm (22.4%) for the SE-DPO, 17.0mm (17.8%) for the SI-DPO and 11.8mm (9.4%) for the A-DPO.

Impact on global sagittal alignment (Figure 5)

The average change of the SVA after a 15° extension was 12.6cm ± 1.36 for the BEPO, 14.5cm ± 1.71 for the SE-DPO, 13.4cm ± 1.51 for the SI-DPO and 12.6cm ± 1.36 for the A-DPO. The average change of the TPA was 5.8° ± 0.83 for the BEPO, 14.1° ± 0.28 for the SE-DPO, 13.0° ± 0.39 for the SI-DPO and 0.0° ± 0.07 for the A-DPO.

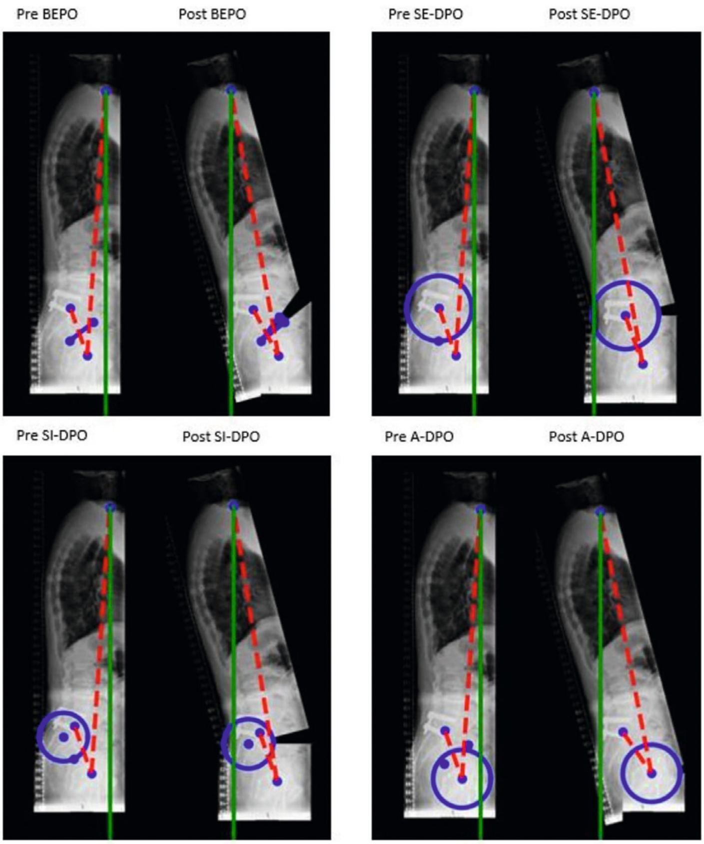

Figure 5.
SVA (green) and the TPA (red) on standing full spine radiographs before and after 15° extension for the BEPO, SE-DPO, SI-DPO and A-DPO. The osteotomy line is visualized in blue.

Table 1. Change of the PSA, percentage bone contact surface and shortening of length of the SSL and STL after 20° extension and change of the SVA and the TPA after 15° extension.

	BEPO	SE-DPO	SI-DPO	A-DPO
Mean ΔPSA in degrees (SD) for				
10°	10,0 (0,00)	10,0 (0,00)	10,0 (0,00)	10,0 (0,00)
15°	15,0 (0,00)	15,0 (0,01)	15,0 (0,01)	15,0 (0,01)
20°	20,0 (0,03)	20,0 (0,02)	20,0 (0,02)	20,0 (0,02)
Mean bone contact in percentage for 20° extension (SD)	-	34,1 (8,87)	28,2 (10,04)	30,6 (4,73)
Ligament shortening for 20° extension in mm (%)				
SSL	2,3 (2,7)	23,6 (27,4)	18,5 (23,5)	7,4 (6,5)
STL	2,4 (1,8)	22,4 (17,5)	15,5 (12,1)	16,3 (12,3)
Average	2,3 (2,2)	23,0 (22,4)	17,0 (17,8)	11,8 (9,4)
Mean ΔSVA in cm for 15° extension (SD)	12,6 (1,36)	14,5 (1,71)	13,4 (1,51)	12,6 (1,36)
Mean ΔTPA in degrees for 15° extension (SD)	5,8 (0,83)	14,1 (0,28)	13,0 (0,39)	-0,1 (0,07)

Discussion

In the present study, we compared four different novel pelvic osteotomies to correct spinopelvic parameters for the correction of sagittal spine balance in an in-silico 2D and 3D model. All variants of the pelvic osteotomies had the same predictable and calculatable effect on extension. The average bone contact surface after 20 degrees extension was the highest for the SE-DPO but with the highest SD. The bone contact surface for the A-DPO revealed a more predictable result with the lower SD but still acceptable average contact area. This consistency could be important in the clinical setting. For the BEPO, the bone contact surface was not measured, as bone contact is not present with this procedure. When performing the BEPO in a clinical setting, a custom-made cage should be inserted to stabilize the open wedge construct and simultaneously improve consolidation. Bone contact with this cage could not be compared with the bone contact surface of the DPOs in this study. Although bone contact surface has been a topic of interest in tibial and hallux valgus correction osteotomies, no minimal percentage of bone contact to maintain stability and good healing conditions could be found in the current literature to compare with.[20-23]
In the current study, the PSA was developed as a novel parameter to quantify the effect of the osteotomies on the pelvic extension because the PI, with only one reference point below the osteotomy, is inadequate for that purpose. Bodin et al. concluded the same principle in a Chiari osteotomy comparable to the A-DPO, where there was no change in PI.[24] The PSA is independent of the position of the patient, changes similar

to the pelvic extension angle and the landmarks can be identified robustly. Even more, the PSA is directly correlated to the sacral slope (SS) following the formula: PSA = 180 – SS – α, where α is the angle between the lower line of the PSA angle and the (vertical) APP.[25-27] For all four pelvic osteotomies, the mean change of the PSA was indeed similar to the angle of the osteotomy. To assess the effect on the global sagittal alignment, we measured the change in the TPA and the SVA in a 2D simulation model (Figure 5). Although this simulation was less precise than the 3D simulation due to difficulty in identifying the anatomic landmarks due to over-projection, it does give a better insight into the clinical effect. In this simulation, we found a normalization (<5cm) of the SVA after 15° of extension for all four osteotomies, which is correlated with improved health-related quality of life measures.[28-31] Correction of the TPA was far less and not within a normal range (6.4° ± 6.2).[32] Probably similar to the PI, the TPA is not ideal as it relies on the hip center and consequently does not change significantly after an A-DPO. In general, a TPA of <20° is accepted as well-aligned, although a surgical target of <°10 is proposed because of post-surgical deterioration of the correction in patients with a higher TPA.[33]

An important consideration for the clinical implication is surgical feasibility, including surgical approach, risk of sciatic nerve impingement and loss of strength of the sacropelvic ligaments. An anterior approach is proven to be safe and feasible since this is like the approach for a Pemberton or Chiari osteotomy.[34] The main advantage of a DPO over an open-wedge osteotomy is the combined ability to correct the alignment while maintaining bone contact.[35,36] Another important advantage of a pelvic osteotomy is that it does not rely on a posterior hinge that can easily fracture and create instability, especially in osteoporotic bone. On the other hand, a successful posterior hinge would provide stability and lower the risk of injury to or impingement of the sciatic nerve.

A disadvantage of the dome osteotomies is the significant shortening of the SSL and STL, especially after the SE-DPO and SI-DPO. Average shortening of 23.0% and 17.0% respectively suggest loss of strength of these ligaments which can lead to pelvic organ prolapse. The shortening of the ligaments after the BEPO (2.3%) and the A-DPO (11.8%) is probably acceptable in the clinical setting; however, there was no recent literature available about the effect on the strength after this amount of shortening. Various gynecologic researchers have studied the SSL and STL to prevent or treat pelvic organ prolapse. Cosson et al. performed a cadaveric test to compare the maximal strength of different pelvic ligaments. They found the prevertebral and iliopectineal ligaments significantly stronger than the SSL and STL,[37] which suggest that a DPO would not have so much impact on potential pelvic organ prolapse. On the other hand, studies about pelvic traumatic injuries proved an important role in the stability of the pelvis.[38-40] Under normal circumstances, only elderly patients would be eligible for this procedure, so there is no risk for problems during future pregnancies.

The biggest limitation of our study is that we could only simulate the effect of the bony correction. The segmentated pelvises could not be tested for the effect on the

strength of the pelvic ligaments or impingement of the sciatic nerve. This study is not a full biomechanical analysis and mainly focuses on the geometrical aspects. Another limitation is the less accurate measurement of the global sagittal alignment on the standing full spine radiographs due to lower image resolution and over-projection.
In conclusion, we found a clear and comparable effect on pelvic extension for all four osteotomies. The A-DPO shows the lowest risk for hinge fracture with the highest bone contact surface. The BEPO, however, is an established osteotomy type with less effect on the shortening of the spinopelvic ligaments. The effect on global sagittal alignment has yet to be established, although based on our 2D simulation, the correction of the SVA is the biggest after the SE-DPO. Both the A-DPO and the BEPO could be eligible alternative procedures to a lumbar osteotomy for the correction of severe rigid sagittal disbalance. However, further studies should be conducted to assess anatomical feasibility and safety.

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III

SUMMARY AND GENERAL DISCUSSION

7

Summary and general discussion

SUMMARY

This thesis aimed to evaluate the effectiveness of surgical treatment options to correct spinal malalignment and explore various concepts of pelvic osteotomies as a potential alternative to spinal correction osteotomies. The thesis was divided into two parts to answer the research questions formulated in the general introduction.

Part I: Current evidence

Is there a correlation between corrected sagittal alignment of the spine and patient-reported outcomes measurements in patients with lumbar degenerative disorders?

The relationship between surgical correction of sagittal spinal alignment and patient-reported outcomes was evaluated through a systematic review and meta-analysis in **Chapter 2**. The study analyzed 34 observational studies involving 973 patients. Among the spinopelvic parameters examined, PT emerged as a key indicator, with significant correlations identified between reduced PT and improvements in the ODI and VAS scores. These findings highlight the importance of addressing PT during surgical planning to achieve optimal outcomes. However, the review revealed limitations in the available evidence, including methodological heterogeneity and a lack of randomized controlled trials.

What is the current practice and influence of sagittal spinal alignment on the decision-making among spine surgeons in the Netherlands?

In **Chapter 3**, a survey conducted among Dutch spine surgeons revealed a broad awareness of the importance of sagittal balance in managing spinal disorders. While orthopedic surgeons demonstrated a higher adoption rate of spinopelvic parameters in decision-making, neurosurgeons applied these principles less consistently. These parameters were recognized as crucial for surgical planning, yet their application in routine practice varied. This disparity between theoretical knowledge and clinical implementation indicates a need for standardized diagnostic protocols and surgeon training.

Part II: Surgical treatment options

Which posterior surgical technique is most appropriate to achieve adequate lumbar lordosis restoration in patients with degenerative disorders?

Chapter 4 describes an experimental study on cadaveric models to compare different surgical approaches for restoring lumbar lordosis. The different steps of posterior element resections as part of posterior interbody fusion each contributed statistically significantly to the restoration of segmental lordosis, with bilateral facetectomy contributing the most in percentage.

Is a bilateral anterior open-wedge correction osteotomy of the ilium effective in changing the pelvic incidence (PI) to correct sagittal malalignment of the spine?
Chapter 5 investigated the feasibility of reducing PI through a novel bilateral anterior open-wedge osteotomy of the ilium, termed BEPO. The BEPO effectively reduced PI, offering a promising alternative for correcting sagittal imbalance, particularly in cases where lumbar osteotomies are insufficient. The anatomical feasibility of the technique was supported, although correction was limited and clinical validation is necessary.

What is the feasibility of different pelvic dome osteotomies compared to an open wedge pelvic osteotomy when tested in an in-silico model?
In **Chapter 6**, various pelvic osteotomies were compared in an in-silico model. A-DPO appeared to be the most predictable and reliable DPO. However, it is technically demanding and shortens the pelvic floor ligaments. BEPO is less demanding and has minimal effect on the ligaments but requires more complex stabilization methods.

GENERAL DISCUSSION

The human evolution to bipedalism represents a key milestone in our evolutionary history, offering significant advantages such as freeing the hands for tool use and enhanced vision.[1] Fossil evidence indicates that this transition began over six million years ago, with anatomical adaptations such as a forward-shifted foramen magnum to balance the head above the spine, elongated lower limbs and arched feet for efficient locomotion.[2,3] Changes in the pelvis and spine were particularly critical, enabling the upright posture characteristic of bipedalism.[4] While these adaptations provided many advantages, they also introduced spinopelvic pathologies unique to humans.

The spatial orientation of the sacrum relative to the lumbar spine has been shown to be of great importance for the sagittal spinal alignment. Pelvic retroversion, characterized by increased PT and decreased SS, helps achieve a balanced standing posture with other spinal parameters within the normal range. Therefore, this parameter is pivotal in analyzing sagittal spinal malalignment. In **Chapter 2**, a systematic review of the literature and meta-analysis to investigate the correlations between spinopelvic parameters and clinical outcome, PT was the most strongly correlated radiological parameter. A decrease of PT was significantly related to improvement in the ODI and the VAS for pain in patients who were treated surgically for lumbar degenerative disorders. Unfortunately, all the included studies were observational and the correction of sagittal malalignment was not the primary aim in most studies. Therefore, the results may be confounded by other conditions that were treated, such as painful spondylolisthesis, and the correction of sagittal malalignment was just a side-effect of the surgery. Nonetheless, the results of the regression analysis indicated a correlation between lower PT and decreased disability and pain, suggesting a causal relationship. Many other researchers have tried to identify the correlation between sagittal spinal malalignment and decrease in HRQOL. Several studies have shown that improved HRQOL is associated with adequate restoration of sagittal malalignment.[5-8] However, with the wide variety of spinal alignment in the asymptomatic population, which becomes even wider during aging, it is still an inconsistent predictor for clinical outcomes. Moreover, only two of the 20 relations available in **Chapter 2** were statistically significant. This meta-analysis was at that time the best evidence of a correlation between improved spinopelvic parameters after surgical correction and improved clinical outcomes. The importance of pelvic retroversion, which means effectively the hyperextension of the hip joints, is even more evident in patients with severe hip osteoarthrosis, who are not able to (hyper)extend the hips and therefore have a higher risk of unbalanced spinal alignment.[9] Although the first studies to address the correlation between sagittal spinal malalignment and clinical outcome were published in the late 1990s and early 2000s, a survey among spine surgeons in the Netherlands in 2015 found a limited clinical application, especially among neurosurgeons (**Chapter 3**). By then, 84% of orthopedic surgeons and 27% of neurosurgeons said they would apply the theory of sagittal alignment in their clinical practice. Still, only a limited group (42%) thought that the clinical outcomes would improve as a result of using sagittal alignment as a factor for the decision-making. With the increasing recognition of the importance of sagittal spinal alignment in recent years, these results might be different in a new survey.

This thesis explored various techniques to address sagittal spinal malalignment. Regional changes such as loss of LL as a result of DDD or after surgical decompressive interventions, also known as iatrogenic flatback deformity[10], can be treated using LIF with some correction of this deformity. Different surgical techniques have been evaluated for surgical outcome, including the correction of spinopelvic parameters.[11-15] Yoon et al. compared the ALIF, the OLIF and the TLIF and did not find significant differences in postoperative PI – LL mismatch, PT and SVA at one-year follow-up.[15] These findings conflict with previous studies demonstrating the superiority of an ALIF technique compared with posterior approaches in terms of correction of spinopelvic parameters, especially LL.[16-19] This conflict was mainly explained by the relatively high correction that was found in this study for the TLIF, which could be explained by the bilateral facetectomy that was performed during this procedure, allowing posterior column shortening in addition to anterior column lengthening, followed by rod assembly under compression. This is similar to the setup of the cadaveric study presented in **Chapter 4**, where a bilateral facetectomy was performed as part of a posterior lumbar interbody approach and compression was given over the pedicle screws after each successive step. Bilateral facetectomy significantly contributed to lordosis restoration (+3.4°, 20%), underlining the results of Yoon et al. However, the excision of too much of the bony elements may lead to spinal instability and nonunion. A resection of more than 30% led to increased spinal mobility, facet loading and intradiscal pressure in a finite element model.[20] Remarkably, there was no difference between unilateral and bilateral facetectomy. Another cadaveric biomechanical study confirmed the potential improvement in sagittal alignment after complete bilateral facetectomy with similar results (+3.74°).[21] Spinal instability is mainly reported after a stand-alone discectomy or laminectomy to achieve neural decompression. This may result in loss of LL or even lumbar kyphosis, leading to revision surgery if not combined with spinal fusion.[22]

Sacral and pelvic osteotomies were first proposed as a method for restoring spinal deformities by Doherty in 1973[23] and later by Bodin and Roussouly in 2014[24]. Traditionally, correction of spinal malalignment was always performed within the spine. A correction osteotomy is most often performed in the lumbar spine, but there is no consensus on the appropriate osteotomy level.[25] A biomechanical analysis found that the impact of a spinal osteotomy on the SVA is determined by both the correction angle and the osteotomy level, with smaller correction angles required when the osteotomy is performed at lower spinal levels.[26] This is underlined in a systematic review describing the effectiveness of a sacral osteotomy on restoring sagittal spinal malalignment for patients with flat back deformity and a high PI.[27] In van Royen's analysis, a mathematical method was developed for deformity planning for the correction of sagittal malalignment in ankylosed spine cases. At that time, the role of sacral orientation in sagittal spinal alignment was newly recognized, with the sacral endplate angle (SEA) being incorporated into the analysis. Based on this, a pelvic osteotomy could be a very promising alternative to correct sagittal malalignment. Although in that study, the osteotomy was performed at L4, the effect of a potentially more caudal osteotomy with the same correction angle can be perceived. The nonogram in Figure 1 was derived from the study by van Royen[26] and shows for case 1 (A) an SVA of 50mm instead of 100mm when the osteotomy was performed at level S1 instead of L3, with the same correction angle of 30°. This suggests that normalization of the SVA could be achieved with a correction angle of only 15° when the osteotomy would be performed below the sacral endplate. Such an osteotomy can be achieved with angulation within the pelvis, that is, a pelvic osteotomy.

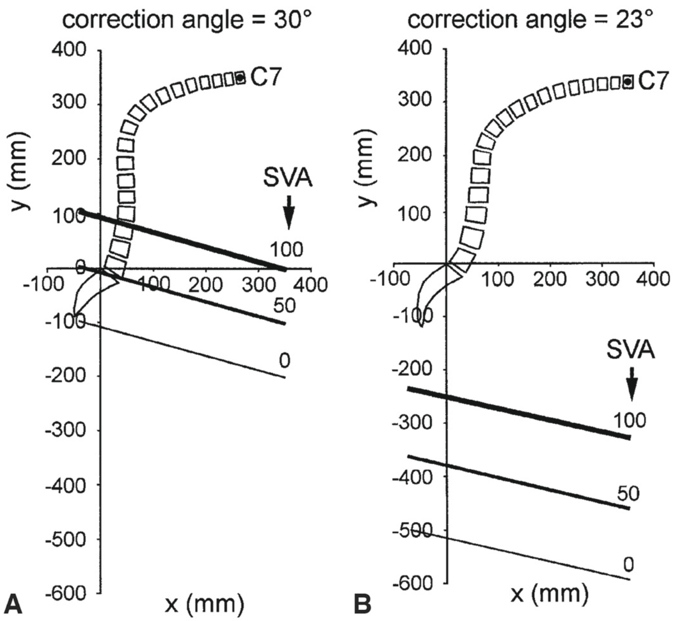

Figure 1. Nonograms constructed from the mathematical model from case 1 (A) and case 2 (B) for the sagittal spine.
Reproduced from Van Royen BJ et al. Deformity planning for sagittal plane corrective osteotomies of the spine in ankylosing spondylitis. Eur Spine J. 2000;9(6):492-498.[25]

The effect of different types of pelvic osteotomies on sagittal spinal alignment was elaborated in both a cadaveric study (**Chapter 5**) and an in-silico study

(**Chapter 6**). In **Chapter 5**, the concept of a BEPO was introduced. The effect on PI of this bilateral open-wedge correction osteotomy of the ilium was evaluated on ten human specimens. An effective change of PI of -10.4° was found after a correction angle of 15°. In the computer simulation that was performed, an osteotomy angle of 10° resulted in a decrease of PI of 7° and SVA of 73.21mm. Such a decrease of PI could reduce the PI-LL mismatch and might lead to a decrease of PT. Although PI-LL ±9° is a generally accepted goal for optimal surgical correction,[28] a correction analysis of PI-LL mismatch according to PI in asymptomatic volunteers found that PI-LL should be considered based on PI.[29] Based on their linear regression analysis, PI-LL should be given by the formula: -28.5 + 0.44 x PI. This means that for a PI higher than 64°, a PI-LL above 10 can be a normal value. However, in the aforementioned simulation, PI-LL is still 49° after the BEPO of 10°. This simulation could not correct for compensation mechanisms such as pelvic retroversion and knee flexion, so the effect on PT could not be reliably measured. However, this suggests that a bigger correction angle would be needed to have a clinically relevant effect on the sagittal spinal alignment.
Although the BEPO results in **Chapter 5** were statistically significant and proved our concept, the clinical feasibility and relevance have yet to be established. Because of the substantial risks, including posterior hinge fracture and subsequently a compromised PI correction, the BEPO was in-silico compared with three alternative DPOs in both a 3D and a 2D model (**Chapter 6**). The correction of the pelvic extension was in all procedures similar to the correction angle. A novel parameter, PSA, was used to measure all different techniques because PI was unchanged with this strategy. The change of PSA was similar to the correction angle. This was also predicted for PI change after BEPO in **Chapter 5**, but the correction was partly lost, possibly because a general PLIF cage was used that was not specifically designed for this osteotomy. The preservation of the correction after a DPO should be tested in a cadaveric study in the future. One of the advantages of the in-silico method is the possibility to measure bone contact surface. In a DPO, the stability and union of the construct rely on the amount of this surface. The A-DPO was found to have the best predictable result with an acceptable bone contact surface (30.6%, SD 4.73) compared to the SE-DPO and the SI-DPO (Figure 2, **Chapter 6**). As a result of the open-wedge technique in the BEPO, no bone contact surface could be measured. The stability of this construct would be supported by the posterior hinge and a patient-specific cage. Unfortunately, the unpredictable nature of posterior hinge fractures presents a considerable challenge in clinical practice. In contrast, a DPO eliminates dependence on the posterior hinge, potentially leading to more reliable clinical outcomes.

Conclusion

The evolution of bipedalism and its associated anatomical adaptations highlight a complex interplay between advantages and challenges. This thesis explored the challenges and possible solutions related to the restoration of sagittal spinal malalignment. The findings underscore the significance of surgical correction techniques, particularly the role of innovative approaches like the BEPO and DPO. Despite advancements in surgical methods and alignment theories, there remain gaps in understanding the variability of spinal alignment and its implications for the clinical outcome. Future studies should aim to establish the clinical relevance of these novel techniques.

Future perspectives

The novel surgical techniques to correct sagittal spinal malalignment introduced in this thesis show promising results in pre-clinical studies. However, clinical studies are required to establish the feasibility, safety and effectiveness of restoration of the global sagittal spinal alignment of such pelvic osteotomy techniques. Studies exploring the relationships between spinopelvic parameters, correction angles and osteotomy levels will refine procedural techniques. Long-term follow-up will be critical in evaluating the durability of corrections and their impact on patient-reported outcomes, including quality of life and disability metrics. Additionally, integrating advanced imaging modalities, such as 3D reconstruction and intraoperative navigation, may improve surgical precision and reduce operative risks. Overcoming current limitations, including risks related to posterior hinge fractures and achieving stable corrections, remains a priority. Innovations in fixation techniques, fusion methods and postoperative rehabilitation protocols will be crucial in addressing these challenges.

Personalized medicine is poised to play a transformative role in the field. Individualized approaches, guided by patient-specific anatomical and clinical characteristics, will optimize outcomes. Machine learning algorithms may offer predictive insights, enabling tailored interventions that account for the variability in spinal alignment and compensatory mechanisms such as pelvic retroversion and knee flexion.

Through continued research, technological advancements and interdisciplinary collaboration between orthopedic surgeons, biomechanical engineers and radiologists, pelvic osteotomies can potentially become a reliable and widely adopted solution for the surgical correction of sagittal spinal malalignment.

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8

Summary in Dutch

Nederlandse samenvatting

NEDERLANDSE SAMENVATTING

De vorm van de wervelkolom van de mens is uniek ten opzichte van primaten die op vier poten lopen. Als het zwaartepunt van het lichaam binnen het steunvlak valt, is het lichaam in evenwicht, waardoor er sprake is van een energie-efficiënte situatie. Tijdens de evolutie van de mens van viervoeters naar tweevoeters ontstonden er een aantal anatomische veranderingen van de wervelkolom en het bekken om deze positie lang(er) vol te kunnen houden. In het sagittale vlak leidde dit tot de typische S-vorm van de wervelkolom, bestaande uit de cervicale lordose (CL), thoracale kyfose (TK), lumbale lordose (LL) en sacrale kyfose. In het bekken, dat gezien kan worden als de onderste wervel, ontstond een vijfde bocht: lordose tussen het os ischium en het os ilium. Degeneratieve afwijkingen van de wervelkolom en heupen, wervelfracturen, neuromusculaire afwijkingen en chirurgische interventies kunnen leiden tot abnormale bochten van de wervelkolom en een veranderde sagittale uitlijning van de wervelkolom. Deze groep van aandoeningen wordt *adult spinal deformity* (ASD) genoemd.
Het lopen op twee benen heeft evolutionair veel voordelen opgeleverd voor de mens, aangezien de armen en handen voor andere taken gebruikt konden worden dan voortbewegen. Maar het levert ook uitdagingen op omdat er in bipedale positie grotere krachten op de wervelkolom komen: schuifkracht aan de dorsale zijde en de zwaartekracht aan de ventrale zijde van de wervelkolom. Dit leidt tot pathologie die alleen bij mensen wordt gezien, zoals de ziekte van Scheuermann en scoliose. Door degeneratie van de wervelkolom kan de LL afnemen en de TK toenemen waardoor het zwaartepunt van het lichaam naar voren komt. Deze veranderingen leiden ook weer tot toename van degeneratie, door compensatiemechanismen zoals hypokyfose van de thoracale wervelkolom, hyperlordose van de lumbale wervelkolom, extensie van het bekken, flexie van de knieën en extensie van de enkels.
Chirurgische correctie van ASD is geassocieerd met een hoog complicatierisico. Met name pseudoartrose en kyfose proximaal van de chirurgische correctie komen veel voor. Optimale correctie maakt de kans op complicaties kleiner, maar kan bij grote preoperatieve afwijkingen chirurgisch uitdagend zijn. In sommige gevallen zou een osteotomie van het bekken daarom een alternatief voor een osteotomie van de wervelkolom kunnen zijn.

De studies die in dit proefschrift worden gepresenteerd hebben als doel de effectiviteit van chirurgische behandelopties voor het corrigeren van een afwijkende sagittale uitlijning van de wervelkolom te evalueren op basis van patiënt gerapporteerde uitkomsten. Daarnaast worden verschillende varianten van een osteotomie van het bekken onderzocht als een potentieel minder invasief alternatief voor spinale correctieosteotomieën. Verschillende concepten van een dergelijke bekkenosteotomie werden gesimuleerd in zowel in-silico als kadaveropstellingen. In **Hoofstuk 1** zijn hiervoor verschillende onderzoeksvragen geformuleerd, onderverdeeld in twee delen. Het eerste deel (**Hoofdstuk 2-3**) onderzoekt de huidige stand van bewijs met betrekking tot de klinische relevantie van sagittale spinale uitlijning. Het tweede deel (**Hoofdstuk 4-6**) bespreekt behandelingsopties voor het corrigeren van afwijkingen van de sagittale uitlijning.

In **Hoofdstuk 2** is door middel van een systematisch literatuuronderzoek gekeken naar de relatie tussen chirurgische correctie van sagittale uitlijning van de wervelkolom en door patiënten gerapporteerde uitkomsten. De studie analyseerde 34 observationele onderzoeken waarbij 973 patiënten betrokken waren. Van de onderzochte radiologische parameters kwam *pelvic tilt* (PT) naar voren als een belangrijke indicator, met significante correlaties tussen verminderde PT en verbeteringen in patiënt gerapporteerde uitkomsten (ODI en VAS score). Deze bevindingen benadrukken het belang van het meenemen van PT tijdens de chirurgische planning om optimale resultaten te behalen.

Vervolgens worden in **Hoofdstuk 3** de resultaten van een enquête onder Nederlandse wervelkolomchirurgen over het belang van sagittale uitlijning bij de behandeling van spinale aandoeningen besproken. Deze enquête liet zien dat orthopedisch chirurgen vaker dan neurochirurgen de radiologische parameters die de sagittale uitlijning meten in de besluitvorming lieten meebepalen. Deze parameters werden door het grootste deel van de deelnemers als cruciaal erkend voor de chirurgische planning, maar de toepassing in de praktijk varieerde. Deze discrepantie tussen theoretische kennis en klinische toepassing geeft aan dat er behoefte is aan gestandaardiseerde diagnostische protocollen en gespecialiseerde fellowships.

In **Hoofdstuk 4** wordt een experimentele studie beschreven waarbij op humane kadavers de verschillende chirurgische stappen voor het corrigeren van de LL tijdens een spondylodese werden vergeleken. De resectie van verschillende elementen als onderdeel van een posterieure lumbale interbody fusie (PLIF) droegen elk statistisch significant bij aan het herstel van de segmentale lordose, waarbij de bilaterale facetectomie procentueel het meest bijdroeg.

Hoofdstuk 5 beschrijft een kadaverstudie waarbij door middel van een nieuwe techniek, de bilaterale anterieure open-wig osteotomie van het ilium (*bilateral extending pelvic osteotomy,* BEPO), het verlagen van de *pelvic incidence* (PI) werd onderzocht. De BEPO verminderde PI effectief en biedt een veelbelovend alternatief voor het corrigeren van een afwijkende sagittale uitlijning, met name in gevallen waarbij er met een lumbale osteotomie niet voldoende correctie behaald kan worden. De anatomische haalbaarheid van de techniek was voldoende, maar de correctie was beperkt en de resultaten moeten nog klinisch gevalideerd worden.

Als vervolg op de studie in Hoofstuk 5, worden in **Hoofdstuk 6** verschillende opties van een bekkenosteotomie vergeleken in een in-silicomodel. De *dome pelvic osteotomy around the acetabulum* (A-DPO) bleek de meest voorspelbare en betrouwbare DPO te zijn. Deze techniek is echter technisch veeleisend en verkort de ligamenten van de bekkenbodem. De BEPO is minder veeleisend en heeft een minimaal effect op de ligamenten, maar vereist complexere stabilisatiemethoden.

8

9

List of Abbreviations

Acknowledgments - Dankwoord

Curriculum Vitae

LIST OF ABBREVIATIONS

A-DPO	dome pelvic osteotomy around the centers of the acetabula
ALIF	anterior lumbar interbody fusion
ALL	anterior longitudinal ligament
AS	ankylosing spondylitis
ASD	adult spinal deformity
ASIS	anterior superior iliac spine
BDBO	bone-disc-bone osteotomy
BEPO	bilateral extending pelvic osteotomy
C2I	C2 incidence angle
C7pl	C7 plump line
CL	cervical lordosis
DDD	degenerative disc disease
DPO	pelvic dome osteotomy
DSS	Dutch Spine Society
EQ-5D	EuroQol-5 dimensions
GAP	Global Alignment and Proportion score
HRQOL	health-related quality of life
IIA	ischio-iliac angle
JOA	Japanese Orthopedic Association
LBP	low back pain
LFA	lumbofemoral angle
LIF	lumber interbody fusion
LL	lumbar lordosis
MCID	minimal clinically important difference
ODI	Oswestry Disability Index
OLIF	oblique lumbar interbody fusion
PI	pelvic incidence
PJK	proximal junctional kyphosis
PL	pelvic lordosis
PLF	posterolateral fusion
PLIF	posterior lumbar interbody fusion
PROM	patient-reported outcome measurement
PSA	public sacral angle
PSO	pedicle subtraction osteotomy
PT	pelvic tilt

RMDQ	Roland-Morris Disability Questionnaire
SE-DPO	dome pelvic osteotomy around the sacral endplate
SF	Short Form
SI-DPO	dome pelvic osteotomy around the sacroiliac joints
SK	sacral kyphosis
SPA	spinopelvic angle
SPO	Smith-Peterson osteotomy
SRS	Scoliosis Research Society
SS	sacral slope
SSA	spinosacral angle
SSL	sacrospinous ligament
STL	sacrotuberous ligament
SVA	sagittal vertical axis
Th1-SPi	T1 spinopelvic inclination
Th9-SPi	T9 spinopelvic inclination
TK	thoracic kyphosis
TLIF	lumbar interbody fusion
TPA	T1 pelvic angle
VAS	Visual Analog Scale
VCR	vertebral column resection
XLIF	extreme/lateral lumbar interbody fusion

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CURRICULUM VITAE

Alida Elisabeth Anna (Lidewij) was born on November 8th, 1987 in Rotterdam, the Netherlands. She graduated from high school (Gemeentelijk Gymnasium, Hilversum) in 2005. After a gap year in Cambridge, United Kingdom and Accra, Ghana, she started medical school at Leiden University, the Netherlands in 2006.

After graduating in 2013, Lidewij started her medical career at the St. Antonius Hospital in Nieuwegein as a non-training resident at the Department of General Surgery. In 2014, Lidewij began her research career as a researcher/non-training resident at the Department of Orthopedic Surgery at the Diakonessenhuis in Utrecht, the Netherlands (supervisor: dr. S.M. van Gaalen). Here she laid the foundation of this thesis, which resulted in a PhD trajectory under the supervision of prof. dr. F.C. Öner and prof. dr. M.C. Kruyt. She continued her medical career as a non-training resident at the University Medical Center Utrecht (2017) and the Sint Maartenskliniek, Nijmegen (2018).

In 2019, she started her general surgical training at the Máxima Medisch Centrum, Eindhoven/Veldhoven, the Netherlands (supervisor: dr. R.M. Roumen), as part of her specialist training in orthopedic surgery. She continued her orthopedic surgery training at the Máxima Medisch Centrum (supervisor: dr. R.P.A. Janssen) and the Maastricht University Medical Center (supervisor: dr. H.M. Staal). During her residency, Lidewij continued the research for this thesis. She will return to the Máxima Medisch Centrum in 2026 to finish her residency.

Lidewij is married to Joris Crol. They live in Eindhoven with their two children Joppe (2022) and Juliëtte (2024).