# Adolescent idiopathic scoliosis: spinal fusion and beyond

Holewijn, R.M.

2019

***document version***
Publisher's PDF, also known as Version of record

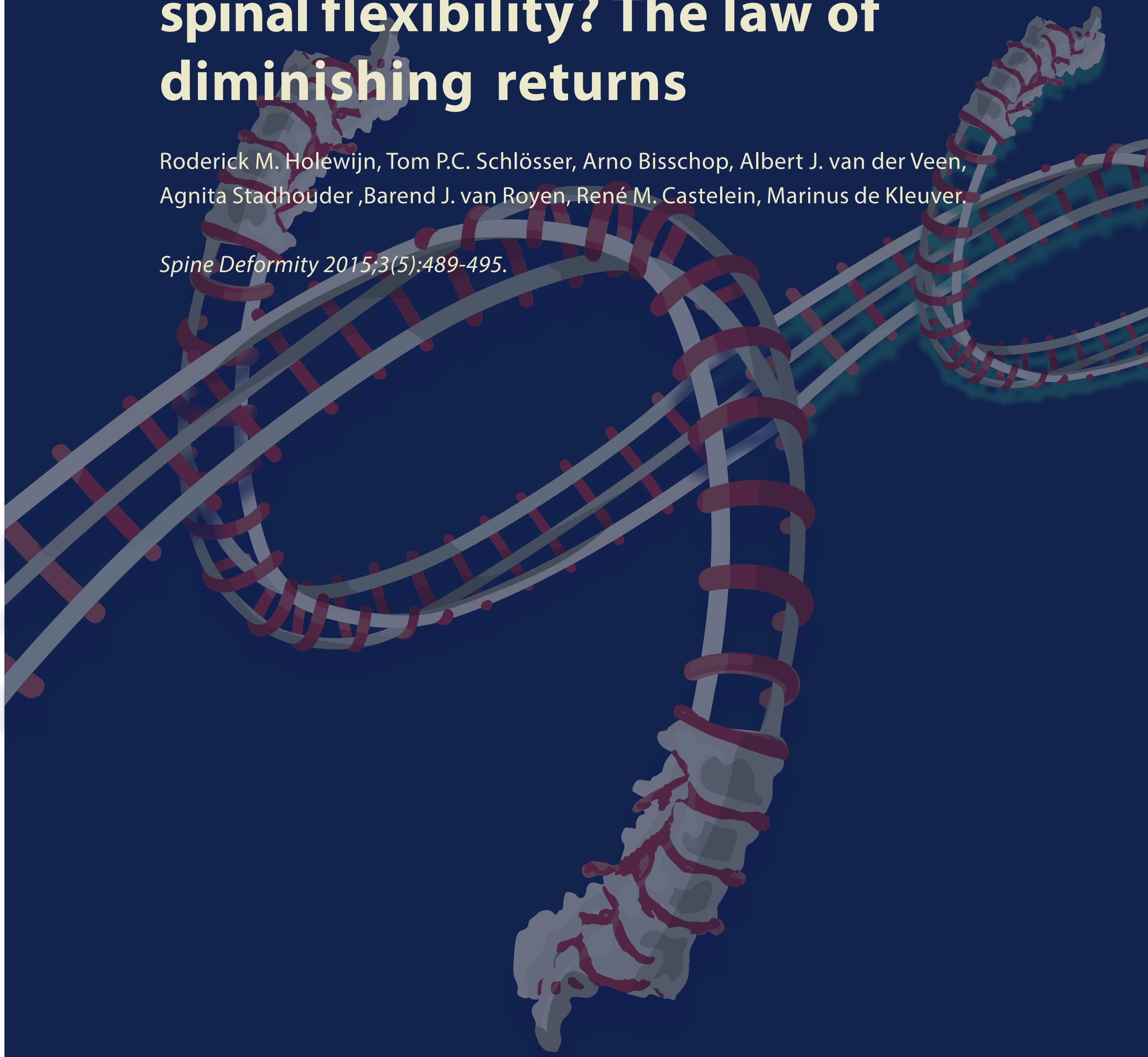
***citation for published version (APA)***
Holewijn, R. M. (2019). *Adolescent idiopathic scoliosis: spinal fusion and beyond*. [PhD-Thesis - Research and graduation internal, Vrije Universiteit Amsterdam].

# Chapter 2

# How does spinal release and Ponte osteotomy improve spinal flexibility? The law of diminishing returns

Roderick M. Holewijn, Tom P.C. Schlösser, Arno Bisschop, Albert J. van der Veen,
Agnita Stadhouder ,Barend J. van Royen, René M. Castelein, Marinus de Kleuver.

*Spine Deformity 2015;3(5):489-495.*



## Abstract

**Objectives:** To evaluate the effect of stepwise resection of posterior spinal ligaments, facet joints, and ribs on thoracic spinal flexibility. Summary of

**Background Data:** Posterior spinal ligaments, facet joints and ribs are removed to increase spinal flexibility in corrective spinal surgery for deformities such as adolescent idiopathic scoliosis (AIS). Reported clinical results vary and biomechanical substantiation is lacking.

**Methods:** Ten fresh-frozen human cadaveric thoracic spinal specimens (T6-T11) were studied. A spinal motion simulator applied a pure moment of 2.5 Nm in flexion, extension, lateral bending (LB) and axial rotation (AR). Range of motion (ROM) was measured for the intact spine and measured again after stepwise resection of the supra/interspinous ligament (SIL), inferior facet, flaval ligament, superior facet, and rib heads.

**Results:** SIL resection increased ROM in flexion (10.2%) and AR (3.1%). Successive inferior facetectomy increased ROM in flexion (4.1%), LB (3.8%) and AR (7.7%), and flavectomy in flexion (9.1%) and AR (2.5%). Sequential superior facetectomy only increased ROM in flexion (6.3%). Rib removal provided an additional increase in flexion (6.3%), LB (4.5%) and AR (13.0%). Extension ROM increased by 10.5% after the combined removal of the SIL, inferior facet and flaval ligament.

**Conclusions:** Posterior spinal releases in these non-scoliotic spines led to an incremental increase in spinal flexibility, but each sequential step had less effect. As compared to SIL resection with inferior facetectomy, additional superior facetectomy did not improve flexibility in AR and LB and only 6.3% in flexion. The data presented from this in vitro study should be interpreted with care, as no representative cadaveric spine model for AIS was available, However, the results presented here at least question the benefits of performing routine complete facetectomies (i.e. Ponte osteotomies) to increase spinal flexibility in scoliosis surgery.

## Introduction

Adolescent idiopathic scoliosis (AIS) is a complex three-dimensional deformity of the spine, characterized by a lateral deviation in the coronal plane, rotation in the axial plane, and alterations of the sagittal profile. During surgical correction of a scoliotic deformity, surgical releases are often performed to increase spinal flexibility and improve deformity correction. Over the past years, the posterioronly approach to the spine has gained popularity, and modern spinal surgery for AIS includes Ponte-type osteotomies and rib releases in order to restore natural spinal alignment [1-6]. Although only recently used in the surgical treatment of AIS, the Ponte or Smith-Petersen osteotomy was first described by Smith-Petersen in 1945 for the correction of thoracic kyphosis resulting from ankylosing spondylitis [7]. Ponte described a similar procedure for correcting the sagittal-plane deformity associated with Scheuermann kyphosis [1]. Both techniques involve the resection of the supraspinous, interspinous, and flaval ligament and the facet joint. More recently, the use of these releases has been described not only for correcting kyphosis but also for correcting coronal and transverse plane deformity.

Clinical series reported promising results using different releases in the surgical treatment of challenging spinal deformities [4,8-10]. Nevertheless, the effectiveness of Ponte osteotomies in gaining spinal flexibility compared to less extensive techniques is not proven. This is illustrated by Halanski et al. who reported that Ponte osteotomies increased operative time and blood loss without a significant improvement in correction of AIS, compared with inferior facetectomies alone [11].

To date, several biomechanical studies assessed the contribution of posterior spinal elements to spinal flexibility [12-16]. Sangiorgio et al. investigated the effect of complete Ponte osteotomies on spinal motion compared to the intact spine and reported an increase in thoracic range of motion in flexion (69%), extension (56%) and axial rotation (34%) but little effect on lateral bending (2%) [17]. The Ponte osteotomy involves multiple steps, including the resection of the posterior spinal ligaments and facet joints. To our knowledge, the individual contribution of each of these structures on spinal flexibility has not been investigated before. Consequently, it remains unclear how much spinal mobility can be gained by each individual step of the release. Feiertag et al. and Yao et al. reported an increase in rotational spinal flexibility after rib mobilizations. However, none of these studies combined rib mobilizations with Ponte osteotomies [13,14], and so it is not known whether rib mobilizations provide additional flexibility compared to a Ponte osteotomy alone.

The main goal of this study was to quantify the contribution of each subsequent step of a Ponte osteotomy on thoracic spinal flexibility. In addition, we investigated the possible further gain in flexibility with bilateral rib removal. To our knowledge, no reliable tools for the intraoperative measurement of applied force and displacement are yet available. As a result, the only way to address the above-mentioned goals in a controlled study, without the influence of interpatient differences (eg, curve magnitude, sagittal profile, age, body mass index, and/or ribcage deformity), is to perform an in vitro study. Because no representative cadaveric in vitro model for adolescent idiopathic scoliosis is available to date, we have used the best model readily available: human cadaveric, nonscoliotic, thoracic spinal specimens.

## Materials and Methods

### Specimens and specimen preparation

Twenty-three human thoracic spinal segments (T6-T11) were harvested from freshly frozen (-20°C) human cadavers (mean age = 73.5 years, standard deviation = 21.2 years). After radiographic evaluation, 13 spinal specimens (56%) with bridging osteophytes or collapsed intervertebral disc spaces were excluded, resulting in 10 healthy specimens available for analysis.

The spines were thawed 12 hours before testing in 0.9% saline-soaked gauzes to prevent dehydration. Excessive muscle tissue was carefully removed, keeping the spinal ligaments, the facet joints, and the posterior 5 cm of the ribs intact. Throughout the experiment, the spinal specimens were kept moist, with 0.9% saline.

The top and bottom vertebrae (T6 and T11) were potted in a casting-mold and partially buried in a low-meltingpoint (48°C) bismuth alloy (Cerrolow-147; 48.0% bismuth, 25.6% lead, 12.0% tin, 9.6% cadmium, and 4.0% indium). The T6 and T11 vertebrae were fixed securely into the alloy by adding screws into the vertebral body. All articulating parts were kept free.

### Biomechanical testing

The test setup was described and validated previously [18]. Before testing, a compressive axial preload of 250 N was applied for 1 hour to obtain physiological conditions in the intervertebral disc [18]. Mechanical testing started immediately after the preloading period. Throughout testing, no compressive load was applied to prevent buckling of the spine. Thoracic spines were placed horizontally in a custom-made four-points bending device (Fig. 1) in which pure moments in flexion, extension, lateral bending (LB), and axial rotation (AR) can be applied, using a hydraulic materials testing machine (Instron, model 8872; Instron and IST, Norwood, Canada). In accordance with literature for biomechanical testing of thoracic spines, loads were increased to +2.5 Nm at an angular velocity of 0.5 degrees/s [19]. At +2.5 Nm, loading was reduced, again at degrees/s, to reach -2.5 Nm. To minimize viscoelastic effects, each movement direction was tested for 10 subsequent cycles [20].

Force and displacement of the Instron machine were recorded and digitized at 100 Hz (Instron Fast Track 2). All tests were performed at room temperature. To correct for order effects, the first five segments were tested in the order FE-LB-AR, whereas the second five segments were tested in the order AR-FE-LB.

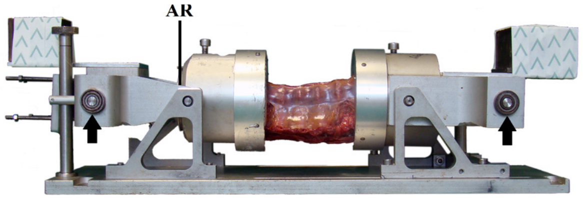


**Fig. 1.** The experimental setup is shown with the thoracic spinal specimen (T6-T11) positioned in the four-points bending device. A materials testing machine applied loads to the two points denoted by the arrows. The specimen was rotated 90º to test lateral bending. To test axial rotation, the left cup was rotated using a steel cable powered by the materials testing machine (AR).

### Testing conditions

Biomechanical testing was first performed on the intact spinal specimens and repeated after each destabilization procedure at levels T7-T10 (Fig. 2). The sequence of successive release procedures before mechanical testing was as follows:

1. Intact

2. Resection of the supra/interspinous ligament (SIL)

3. Bilateral inferior facetectomy (IF)

4. Resection of the flaval ligament (FL)

5. Bilateral superior facetectomy (SF)

6. Bilateral rib removal (RR)

### Data analysis

The range of motion (ROM) of the entire spinal specimen was calculated using load-displacement data of the Instron. The test setup utilizes pure moments as the input and therefore produces the same moment at all the spinal levels. This moment is not affected by an alteration in the spinal specimen, such as the removal of a posterior element. Thus, the response at the nonoperated spinal levels due to the surgical destabilization was not affected, as previously described by Panjabi [21]. Therefore, the change in ROM of the whole spinal specimen after surgical release represented the change in ROM of the three operated motion segments.

In accordance to recent literature, ROM data of the 10th cycle was analyzed [20]. For each direction (FE, LB, and AR), the ROM was calculated from load-displacement data using Matlab (Mathworks, Natick, MA). The ROM was calculated between +2.5 Nm and -2.5 Nm. Each spinal specimen acted as its own internal control, to account for any interspecimen differences in ROM.

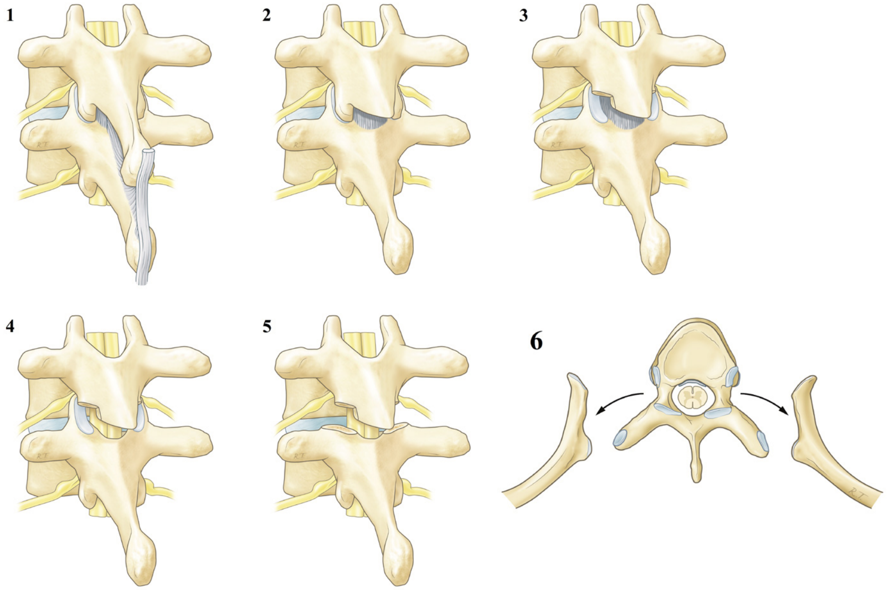


**Fig. 2.** Testing conditions are shown: (1) intact; (2) resection of the supra/interspinous ligament; (3) bilateral inferior facetectomy; (4) resection of the flaval ligament; (5) bilateral superior facetectomy; and (6) bilateral rib removal.

### Statistical analysis

One-way repeated-measures analysis of variance and Holm-Sidak multiple paired comparisons were used to assess the effect of each condition of sequential destabilization on the increase in ROM (% to intact) of the specimens. The P values less than .05 were considered statistically significant.

## Results

The mean absolute and relative ROM after each sequential release is presented in Table 1 and Fig. 3, respectively. Probability values derived from statistical comparisons of relative ROM between each testing condition are presented in Table 2.

### Flexion

In flexion, resection of the SIL complex resulted in a 10.2% increase of the ROM (P = .0015). Sequential inferior facetectomy exhibited an additional increase of 4.1% (+14.3% as compared to the intact condition) (P = .0208). A further increase of 9.1% was observed after flaval ligament resection (P=.0029). Superior facetectomy provided a 6.3% increment (P = .0045), and successive rib release provided a similar increase of 6.3% (P = .0015).

### Extension

In extension, an increase in ROM of 10.5% (P = .0214) was observed after the combined removal of the SIL, inferior facet, and flaval ligament. Sequential superior facetectomy and rib removal did not improve ROM any further (P = .4601 and p= .7800, respectively).

### Lateral bending

No significant increase in ROM was observed after surgical release of the SIL in lateral bending. Successive inferior facetectomy resulted in a significant increase in ROM of 3.8% as compared to intact (P = .0122). Flaval ligament resection and sequential superior facetectomy neither resulted in an increase (P = .2898, and P = .2898). Sequential rib removal did exhibit an additional increase of 4.7% (P = .0097).

### Axial rotation

After SIL resection, a significant increase of 3.1% (P = .0023) in ROM was observed. Added inferior facetectomy caused an additional 7.7% increment, and flaval ligament resection brought an extra 2.5% increase (P = .0001). Successive superior facetectomy did not exhibit any increase in ROM (P = .3753). Sequential rib removal did bring a significant additional increase of 13.0% in ROM (P = .0001).

## Discussion

AIS is a complex three-dimensional deformity of the spine, characterized by lateral deviation in the coronal plane, rotation in the axial plane, and extension of the spine (apical lordosis) in the true sagittal plane [22,23]. Modern scoliosis surgery aims to correct this deformation in all three planes, by translation, derotation, and posterior lengthening of the spine, thus restoring the natural spinal alignment. Removal of posterior elements is used in order to increase flexibility to allow better correction of the deformation. Biomechanical substantiation on this subject is lacking, and clinical evidence for full Ponte osteotomies suggests limited beneficial effects [11]. In order to understand the contribution of different steps in the posterior release, we investigated the ROM after subsequent posterior releases and rib mobilizations in an experimental setup in a sequential order.

We found that the ROM in flexion (kyphosis) and axial rotation increased after resection of the SIL (10.2% and 3.1%, respectively), inferior facets (4.1% and 7.7%, respectively), and flaval ligament (9.1% and 2.5%, respectively). Sequential superior facetectomy only provided a small additional increase in flexion flexibility and no increase in rotation flexibility.

**Table 1** Range of motion in flexion of thoracic spine segment T7-T10: flexion, extension, lateral bending, and axial rotation.

| Measure | Intact | SIL | IF | FL | SF | RR |
|---|---|---|---|---|---|---|
| Flexion (degrees) | | | | | | |
| Mean | 6.4 | 7.0 | 7.3 | 7.8 | 8.1 | 8.5 |
| SD | 3.4 | 3.6 | 4.0 | 3.8 | 3.6 | 3.6 |
| Range | 3.8-15.8 | 4.6-16.9 | 4.7-18.5 | 5.4-18.3 | 5.4-18.1 | 5.6-18.2 |
| Extension (degrees) | | | | | | |
| Mean | 3.9 | 4.1 | 4.3 | 4.4 | 4.4 | 4.5 |
| SD | 1.4 | 1.6 | 1.7 | 1.7 | 1.7 | 1.8 |
| Range | 2.1-6.5 | 2.1-7.0 | 2.2-7.2 | 2.2-7.4 | 2.1-7.6 | 2.1-7.7 |
| Lateral bending (degrees) | | | | | | |
| Mean | 15.5 | 15.7 | 16.1 | 16.2 | 16.4 | 17.0 |
| SD | 6.5 | 6.5 | 6.8 | 6.7 | 6.9 | 7.0 |
| Range | 7.2-31.0 | 7.5-31.1 | 7.6-32.4 | 7.5-31.8 | 7.4-32.8 | 7.8-33.2 |
| Axial rotation (degrees) | | | | | | |
| Mean | 20.8 | 21.4 | 23.0 | 23.5 | 24.2 | 27.0 |
| SD | 5.9 | 6.1 | 6.7 | 7.0 | 7.8 | 9.1 |
| Range | 12.6-31.2 | 13.5-32.2 | 14.8-34.7 | 15.2-35.9 | 13.4-36.9 | 14.2-41.2 |

SIL, supra/interspinous ligament resection; IF, inferior facetectomy; FL, flaval ligament resection; SF, superior facetectomy; RR, rib removal; SD, standard deviation.

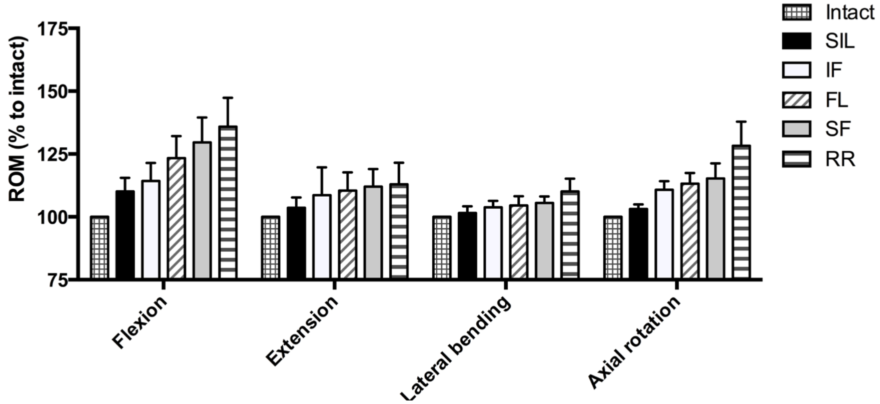


**Fig. 3.** Change in range of motion (% to intact) of the thoracic spinal specimens as a result of sequential release of spinal structures. SIL, supra/interspinous ligament resection; IF, inferior facetectomy; FL, flaval ligament resection; SF, superior facetectomy; RR, rib removal. Error bars indicate standard deviations.

**Table 2** Probability values from statistical comparisons between ROMs (% to intact) of each testing condition.

| | SIL | IF | FL | SF | RR |
|---|---|---|---|---|---|
| Flexion | | | | | |
| Intact | **0.0015** | **0.0011** | **0.0001** | **<0.0001** | **<0.0001** |
| SIL | | **0.0208** | **0.0001** | **0.0001** | **<0.0001** |
| IF | | | **0.0029** | **0.0015** | **0.0006** |
| FL | | | | **0.0045** | **0.0015** |
| SF | | | | | **0.0015** |
| Extension | | | | | |
| Intact | 0.2082 | 0.3259 | **0.0214** | **0.0068** | **0.0171** |
| SIL | | 0.4842 | **0.0067** | **0.0018** | **0.0067** |
| IF | | | 0.7800 | 0.4842 | 0.4003 |
| FL | | | | 0.4601 | 0.3817 |
| SF | | | | | 0.7800 |
| Lateral bending | | | | | |
| Intact | 0.2898 | **0.0122** | **0.0202** | **0.0014** | **0.0017** |
| SIL | | **0.0194** | **0.0194** | **0.0097** | **0.0004** |
| IF | | | 0.2898 | 0.0983 | **0.0045** |
| FL | | | | 0.2898 | **0.0004** |
| SF | | | | | **0.0097** |
| Axial rotation | | | | | |
| Intact | **0.0023** | **<0.0001** | **<0.0001** | **0.0002** | **<0.0001** |
| SIL | | **<0.0001** | **<0.0001** | **0.0023** | **0.0004** |
| IF | | | **0.0016** | 0.1287 | **0.0023** |
| FL | | | | 0.3753 | **0.0046** |
| SF | | | | | **<0.0001** |

SIL, supra/interspinous ligament resection; IF, inferior facetectomy; LF, flaval ligament resection; SF, superior facetectomy; RR, rib removal. Boldface indicates significance.

One of the techniques used during surgery is vertebral derotation [9,24-27]. This technique is often used after Ponte osteotomies have been performed, which are believed to increase axial rotational flexibility, thus making the derotational maneuver more effective. In the present study, the axial rotation represents this vertebral derotation. After the subsequent resection of the SIL, flaval ligament, and inferior facet, a superior facetectomy had no additional value in terms of rotation. A possible explanation is that due to thoracic facet orientation, without direct contact of the two surfaces of the facet joint or restraining joint capsule, a superior facetectomy after an inferior facetectomy is not likely to result in an increase in axial rotation mobility. It remains unclear whether these results are also applicable to the scoliotic spine, where facet joint anatomy varies greatly [28].

Compared to the other destabilizations investigated in this study, rib head releases had the largest effect on axial rotation ROM. The posterior 5 cm of the ribs were left attached to the specimens (ie, the rib cage was not intact), and rib removal increased axial rotation ROM after the Ponte osteotomies with 13.0% (0.9° per spinal segment). The effect during surgery on a patient would probably be much larger, with the large stabilizing effect of the chest cage diminished after partial rib resections. These findings suggest that in severe thoracic deformation cases, if Ponte osteotomies fail to induce sufficient spinal mobility, an additional increase in rotational spinal flexibility can be obtained by performing rib mobilizations.

To date, multiple biomechanical studies have reported significant increases in flexion-extension ROM, ranging from 13% to 45% after complete facetectomies [15,16,29]. Therefore, it is often believed that these osteotomies allow for better restoration of sagittal spinopelvic alignment. However, the effect of a complete facetectomy compared to an inferior facetectomy on the spinal ROM after removal of the supraspinous, interspinous, and flaval ligament has not been investigated before. This study shows that including a superior facetectomy contributes an extra 6.3% (0.1° per spinal segment) as compared to flexion ROM after inferior facetectomy only. This is a minor increase compared to the 23.3% (0.5° per spinal segment) increase in flexion already provided by the combined removal of the posterior ligament complex, inferior facet, and flaval ligament. From a clinical perspective, Halanski et al. showed that superior facetectomy introduces an increase in blood loss, longer operative time, and the risk of nerve root damage, without improving coronal or sagittal correction as compared to inferior facetectomies [11]. From these results and the current study, it seems that an additional superior facetectomy (ie, Ponte osteotomy) will hardly help restoring sagittal alignment. Although it is postulated that these osteotomies could be useful in extremely stiff spines, Halanski et al. discourage the routine use of Ponte osteotomies [11], and this study supports that.

Besides vertebral derotation and restoration of sagittal alignment, coronal correction is an important goal during surgery. We investigated this effect by applying lateral bending moments to the spinal specimen. Flaval ligament resection and sequential superior facetectomy did not provide any benefit after the inferior facet had been removed. Increases of 3.8% and 4.7% were observed after inferior facetectomy and rib removal, respectively. Thus, in addition to axial rotation ROM, rib head release was the most effective procedure to increase lateral bending ROM.

Resection of the SIL, flaval ligament, and complete facetectomies (ie, Ponte osteotomies) increased ROM, with 29.6% (1.7° per spinal segment) in flexion, 12.1% (0.5º per spinal segment) in extension, 5.5% (0.9° per spinal segment) in lateral bending and 15.3% (3.4° per spinal segment) in axial rotation. These results are in agreement with findings of a cadaveric study performed by Anderson et al. [16]. However, Sangiorgio et al. reported a large increase of thoracic ROM after complete Ponte osteotomies in flexion (69%), extension (56%), and axial rotation (34%) but little effect in lateral bending (2%) [17]. Other biomechanical studies reported similar results as Sangiorgio et al. [15,16]. The differences between other studies and our results could be explained by the fact that in this study the ribs were left attached to the spine. The rib heads attach laterally and bridge two vertebras, thereby providing significant stability to the spine. Furthermore, although the average age of the specimens was high (73.5 years) and not all signs of degeneration can be excluded based on plain radiographs, we performed a strict selection of nondegenerative spines: 56% of the available spinal specimens were excluded in this study, whereas the previously discussed literature did not report such selection criteria. This does not exclude minor degeneration in these elderly spines, which will still behave differently compared to scoliotic nondegenerated adolescent spines. Future experimental studies focussed on nondegenerative spinal disorders should perform prior radiologic assessment to exclude degenerated spinal specimens.

One of the major limitations of this study is the advanced age of the specimens used. To limit the effect of age, we only used spinal specimens devoid of intervertebral disc degeneration and bridging osteophytes. Still, there was undoubtedly some remaining form of spinal degeneration present in the specimens used in this study. This results in an increase in spinal stiffness as compared to adolescent spines. Another limitation is that we were unable to obtain specimens with AIS. It is known that the thoracic hypokyphosis or lordosis that is typical in the thoracic spine of AIS patients could potentially be related to shortening or increased stiffness of the posterior spinal ligaments [30]. Therefore, posterior releases during surgery for AIS could potentially be more effective as compared to the results presented here, because it targets the area of pathology. Additionally, it remains unknown what the effect is of posterior surgical releases in different types of scoliotic curves varying in Cobb angle, sagittal alignment, vertebral rotation, and/or rib cage deformation. Consequently, the effect of ligamentous releases observed in this study could be significantly different in surgery for a wide range of different AIS curve types. Additionally, because of technical limitations of our testing setup, we could only keep the posterior 5 cm of the ribs intact and not the whole rib cage. As a result, the stabilizing effects of the rib cage and trunk muscles were not accounted for. Another limitation is that because of the limited amount of spinal specimens available, we could not randomize the order of the surgical releases. The order was chosen to represent common surgical practice for spinal scoliotic deformities. Because the results presented in this study could be partially related to this specific order in which the releases were performed, it is not possible to predict the effects of other techniques based on the data presented here. In this study, rib head releases were the most effective technique to increase lateral bending and axial rotation ROM. However, this was after a Ponte osteotomy was performed. Future studies should investigate whether a different order of the release, for example, starting with the facetectomy, would provide different results. Potentially, starting a posterior release with a rib osteotomy (if in any way feasible) might also provide additional flexibility after the rib heads have been removed. Finally, factors of influence during surgery such as the degree of deformity or any remaining muscle and ligament tension could make the translation of the results to the clinical situation difficult. Despite its known limitations, we have used the best model available to study posterior releases in an in vitro cadaveric experiment. To analyze the actual gains in spinal flexibility provided by posterior releases during AIS surgery, intraoperative in vivo measurements are needed. Despite the limitations, this study provides important data concerning spinal releases, and the results are in line with clinical studies [11].

This study demonstrates that posterior spinal releases used in scoliosis surgery follow the law of diminishing returns: removing more posterior spinal structures does not automatically result in an increase of spinal flexibility. It can therefore be concluded that ROM in flexion, lateral bending, and axial rotation increases by resection of the SIL, inferior facet, and flaval ligament. Superior facetectomy, however, provided only a small additional increase in flexion (kyphosis) and had no value for range of motion in extension, lateral bending, and axial rotation.

In conclusion, although in line with clinical observations, the data presented from this in vitro cadaver study in nonscoliotic spines should be interpreted with care, as no representative cadaveric spine model for AIS was available [11]. However, the results presented here at least question the benefits of performing routine complete facetectomies (ie, Ponte osteotomies) to increase spinal flexibility in scoliosis surgery.

## Acknowledgments

This study was funded by the Anna Foundation (grant number: O2013/53). The authors would like to thank Nick Vincken for his assistance during experiments, Valentijn Holewijn for providing the photographic illustration of the experimental setup, and Rogier Trompert Medical Art for providing the illustrations of the surgical procedures.

## References

1. Geck MJ, Macagno A, Ponte A, Shufflebarger HL. The Ponte procedure: posterior only treatment of Scheuermann's kyphosis using segmental posterior shortening and pedicle screw instrumentation. J Spinal Disord Tech 2007;20:586–93.
2. Suzuki N, Kono K. Super Hybrid Method of scoliosis correction: minimum 2-year follow-up. Stud Health Technol Inform 2010;158:147–51.
3. Shah S, Dhawale A, Oda J, Yorgova P. Ponte osteotomies with pedicle screw instrumentation in the treatment of adolescent idiopathic scoliosis. Spine Deform 2013;1:196–204.
4. Good CR, Lenke LG, Bridwell KH, O'Leary PT, Pichelmann MA, Keeler KA, et al. Can posterior-only surgery provide similar radiographic and clinical results as combined anterior (thoracotomy/thoracoabdominal)/posterior approaches for adult scoliosis? Spine (Phila Pa 1976) 2010;35:210–8.
5. Shufflebarger HL, Geck MJ, Clark CE. The posterior approach for lumbar and thoracolumbar adolescent idiopathic scoliosis: posterior shortening and pedicle screws. Spine (Phila Pa 1976) 2004;29:269–76.
6. Diab MG, Franzone JM, Vitale MG. The role of posterior spinal osteotomies in pediatric spinal deformity surgery: indications and operative technique. J Pediatr Orthop 2011;31:S88-98.
7. Smith-Petersen M, Larson C, Aufranc O. Osteotomy of the spine for correction of flexion deformity in rheumatoid arthritis. J Bone Jt Surg 1945;66:6–9.
8. Geck MJ, Rinella A, Hawthorne D, Macagno A, Koester L, Sides B, et al. Comparison of surgical treatment in Lenke 5C adolescent idiopathic scoliosis: anterior dual rod versus posterior pedicle fixation surgery: a comparison of two practices. Spine (Phila Pa 1976) 2009;34:1942–51.
9. Dobbs MB, Lenke LG, Kim YJ, Luhmann SJ, Bridwell KH. Anterior/posterior spinal instrumentation versus posterior instrumentation alone for the treatment of adolescent idiopathic scoliotic curves more than 90 degrees. Spine (Phila Pa 1976) 2006;31:2386–91.
10. Luhmann SJ, Lenke LG, Kim YJ, Bridwell KH, Schootman M. Thoracic adolescent idiopathic scoliosis curves between 70 degrees and 100 degrees: is anterior release necessary? Spine (Phila Pa 1976) 2005;30:2061–7.
11. Halanski MA, Cassidy J a. Do Multilevel Ponte Osteotomies in Thoracic Idiopathic Scoliosis Surgery Improve Curve Correction and Restore Thoracic Kyphosis? J Spinal Disord Tech 2013;26:1.
12. Wiemann J, Durrani S, Bosch P. The effect of posterior spinal releases on axial correction torque: A cadaver study. J Child Orthop 2011;5:109–13.
13. Feiertag M a, Horton WC, Norman JT, Proctor FC, Hutton WC. The effect of different surgical releases on thoracic spinal motion. A cadaveric study. Spine (Phila Pa 1976) 1995;20:1604–11.
14. Yao X, Blount TJ, Suzuki N, Brown LK, Van Der Walt CJ, Baldini T, et al. A biomechanical study on the effects of rib head release on thoracic spinal motion. Eur Spine J 2012;21:606–12.
15. Oda I, Abumi K, Cunningham B. An in vitro human cadaveric study investigating the biomechanical properties of the thoracic spine. Spine (Phila Pa 1976) 2002;27:E64-70.
16. Anderson AL, McIff TE, Asher M a, Burton DC, Glattes RC. The effect of posterior thoracic spine anatomical structures on motion segment flexion stiffness. Spine (Phila Pa 1976) 2009;34:441–6.
17. Sangiorgio S, Borkowski S, Bowen R. Quantification of increase in three-dimensional spine flexibility following sequential ponte osteotomies in a cadaveric model. Spine Deform 2013;1:171–8.
18. Busscher I, van Dieën JH, Kingma I, van der Veen AJ, Verkerke GJ, Veldhuizen AG. Biomechanical characteristics of different regions of the human spine: an in vitro study on multilevel spinal segments. Spine (Phila Pa 1976) 2009;34:2858–64.

19. Wilke HJ, Wenger K, Claes L. Testing criteria for spinal implants: recommendations for the standardization of in vitro stability testing of spinal implants. Eur Spine J 1998;7:148–54.
20. Bisschop A, Kingma I, Bleys RLAW, Paul CPL, van der Veen AJ, van Royen BJ, et al. Effects of repetitive movement on range of motion and stiffness around the neutral orientation of the human lumbar spine. J Biomech 2013;46:187–91.
21. Panjabi MM. Hybrid multidirectional test method to evaluate spinal adjacent-level effects. Clin Biomech (Bristol, Avon) 2007;22:257–65.
22. Schlösser T, van Stralen M, Brink R, Chu W, Lam T, Ng B, et al. Three-dimensional characterization of torsion and asymmetry of the intervertebral discs versus vertebral bodies in adolescent idiopathic scoliosis. Spine (Phila Pa 1976) 2014:May 28 Epub ahead of print.
23. Nicoladoni C. Anatomie und mechanismus der skoliose. Stuttgart, Ger 1904:1–79.
24. Suk SI, Kim WJ, Lee SM, Kim JH, Chung ER. Thoracic pedicle screw fixation in spinal deformities: are they really safe? Spine (Phila Pa 1976) 2001;26:2049–57.
25. Suk SI, Lee CK, Kim WJ, Chung YJ, Park YB. Segmental pedicle screw fixation in the treatment of thoracic idiopathic scoliosis. Spine (Phila Pa 1976) 1995;20:1399–405.
26. Lehman R a, Lenke LG, Keeler K a, Kim YJ, Buchowski JM, Cheh G, et al. Operative treatment of adolescent idiopathic scoliosis with posterior pedicle screw-only constructs: minimum three-year follow-up of one hundred fourteen cases. Spine (Phila Pa 1976) 2008;33:1598–604.
27. Lee S-M, Suk S-I, Chung E-R. Direct vertebral rotation: a new technique of three-dimensional deformity correction with segmental pedicle screw fixation in adolescent idiopathic scoliosis. Spine (Phila Pa 1976) 2004;29:343–9.
28. Parent S, Labelle H, Skalli W, Latimer B, de Guise J. Morphometric analysis of anatomic scoliotic specimens. Spine (Phila Pa 1976) 2002;27:2305–11.
29. Horton WC, Kraiwattanapong C, Akamaru T, Minamide A, Park J-S, Park M-S, et al. The role of the sternum, costosternal articulations, intervertebral disc, and facets in thoracic sagittal plane biomechanics: a comparison of three different sequences of surgical release. Spine (Phila Pa 1976) 2005;30:2014–23.
30. Veldhuizen a G, Wever DJ, Webb PJ. The aetiology of idiopathic scoliosis: biomechanical and neuromuscular factors. Eur Spine J 2000;9:178–84.