Resect or not to resect: the role of posterior longitudinal ligament in lumbar total disc replacement

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Abstract With regard to the literature, several factors are considered to have an impact on postoperative mobility after lumbar total disc replacement (TDR). As TDR results in a distraction of the ligamentous structures, theoretically the postoperatively disc height and ligamentous integrity have also an influence on biomechanics of a treated segment. The purpose of the study was to evaluate the influence of posterior longitudinal ligament (PLL) resection and segmental distraction on range of motion (ROM). Six human, lumbar spines (L2–L3) were tested with pure moments of ± 7.5 Nm in a spine loading apparatus. The ROM was determined in all three motion planes. Testing sequences included: (1) intact state, (2) 10 mm prosthesis (PLL intact), (3) 10 mm prosthesis (PLL resected), (4) 12 mm prosthesis (PLL resected). The prosthesis used was a prototype with a constrained design using the ball-and-socket principle. The implantation of the 10 mm prosthesis already increased the disc height significantly (intact:

9.9 mm; 10 mm prosthesis: 10.6 mm; 12 mm prosthesis: 12.7 mm). Compared to the intact status, the implantation of the 10 mm prosthesis resulted in an increase of ROM for flexion/extension (8.6° vs 10.8° ; $P = 0.245$) and axial rotation (2.9° vs 4.5° ; $P = 0.028$), whereas lateral bending decreased (9.0° vs 7.6° ; $P = 0.445$). The resection of the PLL for the 10 mm prosthesis resulted in an increase of ROM in all motion planes compared to the 10 mm prosthesis with intact PLL (flexion/extension: 11.4° , $P = 0.046$; axial rotation: 5.1° , $P = 0.046$; lateral bending: 8.6° , $P = 0.028$). The subsequent implantation of a 12 mm prosthesis, with resected PLL, resulted in a significant decrease of ROM in all motion planes compared to the 10 mm prosthesis with intact PLL (flexion/extension: 8.4° , $P = 0.028$; axial rotation: 3.3° , $P = 0.028$; lateral bending: 5.1° , $P = 0.028$). Compared to the intact status, the 12 mm prosthesis with resected PLL only decreased lateral bending significantly while the 10 mm prosthesis with intact PLL increased axial rotation significantly. The resection of the PLL during TDR results in a significant increase of ROM in all three principle motion planes. But it still remains unclear if this increase which is in median not more than 1° may alter the clinical results. Moreover, the destabilizing effect of PLL resection can be reversed using a higher implant. The prosthesis height seems more crucial than PLL preservation to maintain the primary stability after TDR.

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Introduction

The problem of adjacent-segment disease (ASD) following lumbar fusion might be diminished by the development of

non-fusion technology. A survey of these implants was published already by Szpalski et al. [18]. Besides other implants such as posterior dynamic stabilization, nucleus replacement and interspinous devices, the device which best represents the philosophy of spine arthroplasty is the total lumbar disc replacement (TDR).

The main advantage of TDR compared to fusion is that a physiological preservation of motion at the treated segment will reduce the incidence of symptomatic ASD. The potential decrease in ASD is mainly attributed to an assumed unloading of the adjacent segments by avoiding hypermobility [10–13, 16].

Besides other potential influencing factors, the resulting segmental distraction, given by the prosthesis height, and the amount of soft tissue release during implantation, e.g., given by resection or preservation of posterior longitudinal ligament (PLL), are possible parameters which have an effect on the postoperative mobility. Currently, no clear recommendations are given in the literature, neither for the ideal prosthesis height nor for the handling of the PLL during surgery. Delamarter et al. [5] advise to choose the proper prosthesis height by visual control during surgery or using different templates under fluoroscopic control. This advice seems as subjective as the recommendation of David [4] who suggests using the highest possible prosthesis. Similar subjective recommendations can be found when seeking for evidence in case of surgical handling of the PLL during implantation of a TDR. David [4] recommends a weakening of the PLL during implantation of the prosthesis. However, in his publication, he provides neither a rationale for the advised “*weakening of the PLL*” nor a detailed description of the proposed surgical maneuver. Delamarter et al. [5] recommended in case of contracted PLL a release from the posterior vertebral body with a forward-angled curette. In contrast, Bertagnoli and Kumar [1] advise to resect the PLL in case of advanced disc degeneration, to facilitate the mobilization of the segment, and Hopf et al. [6] in case of concomitant disc herniation. But all these recommendations are given without scientific evidence on possible consequences in segmental motion and biomechanics.

Therefore, the aim of the current study was to provide evidence for following pending questions:

1. What is the impact of the PLL in TDR on segmental range of motion (ROM)?
2. What is the impact of segmental distraction which is given by the prosthesis height, on the resulting segmental ROM?

Materials and methods

Specimen preparation

Six fresh-frozen segmental lumbar spines L2–L3 (mean age 38.6 ± 14.9 years) were used for testing. Only specimen without intervertebral disc or osseous pathology and without abnormal anatomy, confirmed on anteroposterior and lateral plain radiographs, was used for further testing. Exclusion criteria were joint space narrowing, anterior/posterior osteophytes and obvious sclerosis. All soft tissues were dissected, keeping the capsules, ligaments, and supporting structures intact. For the fixation in the spine tester, the L2 and L3 vertebra were embedded in Polymethylmethacrylate cement (Technovit 3040, Heraeus Kulzer, Wehrheim/Ts, Germany) in such a manner that the L2–L3 disc was in the horizontal plane. The specimens were frozen in triple-sealed plastic bags at -20°C and thawed at 6°C before testing.

Testing protocol

Biomechanical testing of the specimen was performed in a spine tester [21] at room temperature. The cranial vertebra (L2) was mounted to a gimbal, which allowed rotation around all three coordinate axes as well as translation. A traveling gantry and a secondary slide enabled translation in the remaining two planes. The specimens were loaded with pure moments of ± 7.5 Nm in all three principal motion planes with alternating sequences (flexion–extension, left–right lateral bending, left–right axial rotation). No axial preload was applied. This follows the recommendation for the standardized testing of spinal implants [21]. The moments were applied continuously with a constant rate of $1.0^{\circ}/\text{s}$, except for axial rotation ($0.5^{\circ}/\text{s}$). The specimen moved unconstrained in the five uncontrolled degrees of freedom. During loading, the motion at the segment L2–L3 was recorded simultaneously directly in the spine tester.

Four conditions were studied:

1. intact (Fig. 1a);
2. implantation of a TDR with an endplate height of 3 mm (Fig. 1b, c);
3. transforaminal resection of the PLL without removal of prosthesis (Fig. 1d);
4. removal of the prosthesis with 3 mm endplate height and implantation of prosthesis with 5 mm endplate height (Fig. 1e).

For all measurements, two precycles were applied to the specimens and the third cycle was used for data analysis.

Fig. 1 Tested specimen states: intact specimen (a), after preparation of the disc space without resection of posterior annulus fiber/posterior longitudinal ligament complex (PAF/PLL complex) (b), implantation of prototype prosthesis with 6° angulated cranial endplate and 3 mm

caudal endplate height (c), transforaminal view after resection of PAF/PLL complex without removal of the prosthesis (d), implantation of prototype prosthesis with 6° angulated cranial endplate and 5 mm caudal endplate height (e)

Fig. 2 Disc height measurements on lateral fluoroscopic images. **a** Intact specimen, **b** prototype prosthesis with 6° angulated cranial endplate and 3 mm caudal endplate height, **c** prototype prosthesis with 6° angulated cranial endplate and 5 mm caudal endplate height.

Disc height was expressed with the “Dabbs-Ratio”, which is: (anterior disc height + posterior disc height)/2. *AH* anterior disc height, *PH* posterior disc height

The ROM and the neutral zone (NZ) were determined from the third loading cycle. All measurements were performed on the same day.

Measurement of disc height

The measurement of the disc height was performed on lateral fluoroscopic images which were obtained in a standard position with the specimen that was fixed in the spine simulator. Disc heights were expressed with the “Dabbs-Ratio” [3], which is (anterior disc height + posterior disc height)/2 (Fig. 2).

Description of implant and surgical technique

The implant (prototype, Ulrich Medical, Ulm, Germany) has a ball-and-socket joint principle. A 6°-angulated upper endplate was used for all testing sequences. For the different testing sequences, either a 3-mm lower endplate or 5-mm lower endplate was used (Fig. 3).

Implantation was performed by a spine surgeon. Anterior longitudinal ligament and anterior annulus

fibers were excised while preserving the lateral annulus fibers. After complete discectomy, curettage of the cartilaginous endplates without disturbing the osseous endplates was performed. Initially, the complex consisting of posterior annulus fibers (PAFs) and PLL was not excised. The intervertebral space was appropriately mobilized using a distractor. After marking the midline of the lower endplate of L2 and upper endplate of L3 under visual and fluoroscopic guidance, a sagittal groove is then cut in the vertebral endplates in the exact midline using a chisel placed over the trial. The trial is removed, and the final implant is then gently impacted into place using an insertion tool. Final AP and lateral fluoroscopic views were taken to confirm correct position of the prosthesis.

The excision of the PAF/PLL complex, for the third testing sequence, was performed transforaminally without violating the postero-lateral annulus fibers.

For the forth testing sequence, the prosthesis was removed with the insertion tool, and a prosthesis with 5 mm caudal endplate height was implanted as described above.

Fig. 3 Prototype prosthesis with 6° angulated cranial endplate and 3 mm caudal endplate height (a). Prototype prosthesis with 6° angulated cranial endplate and 5 mm caudal endplate height (b)

Statistical analysis

Data were analyzed using the SPSS 12.0 statistical software (SPSS Inc., Chicago, IL, USA). Wilcoxon matched-pairs signed rank test was performed to check for significant differences between the four tested conditions. The significance level was set at $P < 0.05$.

Results

Tables 1 and 2 are summarizing the final results. The median disc height for the intact specimen was 9.9 mm (range 9.3–11.2 mm). The implantation of the prototype with 3 mm caudal endplate resulted in a significant increase of the disc height (median 10.6 mm; range 10.4–12.8; $P = 0.028$). No significant differences could be observed after resection of the PAF/PLL complex (median 10.6 mm; range 10.2–12.8). The implantation of the prototype with 5 mm caudal endplate resulted in a significant increase compared to intact and 3 mm caudal endplate prototype prosthesis (median 12.7 mm; range 12.3–14.0; $P = 0.028$).

The implantation of the prototype prosthesis with 3 mm caudal endplate height regardless of the integrity of the

PAF/PLL complex resulted in an increase of ROM and NZ in flexion/extension and axial rotation whereas lateral bending decreased. With regard to the NZ, these changes were only significant in flexion/extension and axial rotation, whereas the decrease in lateral bending was not significant. With regard to ROM, the change in case of preserved PAF/PLL complex was not significant in flexion/extension and significant in case of resection. For axial rotation, the increase of ROM was significant regardless of the integrity of the PAF/PLL complex. Like for the NZ, the decrease in lateral bending was not significant for both test settings.

The comparison of the prototype prosthesis with 3 mm caudal endplate height with or without resection of the PAF/PLL complex revealed that resection resulted in a significant increase of ROM, whereas almost no effect could be observed with regard to NZ.

The implantation of the prototype prosthesis with 5 mm caudal endplate height resulted in a significant decrease in lateral bending compared to intact status for ROM and NZ. No significant differences were observed in flexion/extension and axial rotation compared to intact.

Comparison of the prototype prosthesis with 5 mm caudal endplate and 3 mm caudal endplate, with or without resection of the PAF/PLL complex, revealed a decrease of

Table 1 Intervertebral ranges of motion (ROM) (in degree) and neutral zone (NZ) (in degree) for the intact and three different test settings

	Flexion–extension (in degree)		Axial rotation (in degree)		Lateral bending (in degree)	
	ROM	NZ	ROM	NZ	ROM	NZ
Intact	8.6 (7.0–11.3)	1.0 (0.5–1.2)	2.9 (2.5–3.8)	0.5 (0.3–0.7)	9.0 (8.3–13.7)	1.0 (0.91.8)
Prototype-3 PLL intact	10.8 (6.0–15.7)	1.5* (1.0–3.0)	4.5* (2.5–7.2)	0.8* (0.6–0.9)	7.6 (3.8–12.5)	0.9 (0.6–2.2)
Prototype-3 PLL resected	11.4* (6.7–16.9)	1.7* (1.1–2.8)	5.1* (2.6–7.5)	0.8* (0.7–1.0)	8.6 (4.4–13.6)	0.9 (0.6–1.9)
Prototype-5 PLL resected	8.4 (5.2–9.9)	1.2 (0.7–1.7)	3.3 (1.9–4.5)	0.6 (0.4–0.7)	5.1* (2.2–6.7)	0.7* (0.5–0.9)

Values are median (minimum–maximum)

Prototype-3 prototype prosthesis with 3 mm caudal endplate height, *prototype-5* prototype prosthesis with 5 mm caudal endplate height, *PLL* posterior annulus fiber/posterior longitudinal ligament complex

* Significant ($P < 0.05$) compared to intact specimen

Table 2 Statistical analysis for the intact specimen and three different test settings

	Flexion–extension (in degree)		Axial rotation (in degree)		Lateral bending (in degree)	
	ROM	NZ	ROM	NZ	ROM	NZ
In versus P3(+)	n.s.	0.046	0.028	0.028	n.s.	n.s.
In versus P3(–)	0.046	0.028	0.028	0.028	n.s.	n.s.
In versus P5(–)	n.s.	n.s.	n.s.	n.s.	0.028	0.028
P3(+) versus P3(–)	0.046	n.s.	0.046	n.s.	0.028	n.s.
P3(+) versus P5(–)	0.028	n.s.	0.028	0.027	0.028	0.046
P3(–) versus P5(–)	0.028	0.028	0.028	0.027	0.028	0.046

In intact specimen, P3(+) prototype prosthesis with 3 mm caudal endplate height, posterior annulus fiber/posterior longitudinal ligament (PAF/PLL) complex preserved, P3(–) prototype prosthesis with 3 mm caudal endplate height, PAF/PLL complex resected, P5(–) prototype prosthesis with 5 mm caudal endplate height, PAF/PLL complex resected

ROM and NZ in all three motion planes for the 5 mm caudal endplate. Except for NZ in flexion/extension for the prototype prosthesis with preserved PAF/PLL complex, all values decreased significantly.

Discussion

The two main observations of the current study could be of profound interest for the clinical setting. (1) Even a slight overdistracted (median increase of 0.7 mm) of the original disc space height (accomplished with the lower prosthesis in the current study) is not able to preserve ROM values of the intact specimen as it results in a hypermobility for flexion/extension and axial rotation (only significant for the axial rotation). (2) Although the resection of the PLL results in a significant destabilization of the segment by means of increase of ROM for all three motion planes, this effect may be reversed using a higher prosthesis. As the results of the current study were obtained with a ball-and-socket principle prosthesis, they cannot be applied to an unconstrained prosthesis, such as, e.g., the Charité prosthesis, without reservation.

The relevance of the obtained results is based on the fact that the proposed fundamental theoretical advantage of TDR over fusion, besides possible advantages in approach-related and donor-site related morbidity [9], is the preservation of segmental mobility [1, 2]. Besides the preservation of mobility per se, the quantity of postoperative ROM after TDR seems also of notably interest as Huang et al. [7] reported a modest but statistically better outcome according to the ODQ (Oswestry Disability Questionnaire) and a modified Stauffer–Coventry score in patients with segmental mobility $>5^\circ$ after a 8.6-year follow-up of patients operated on with a Prodisc prosthesis. On the other hand, it is also proposed that an unphysiological hypermobility after TDR might have detrimental consequences in long term. Huang et al. [7] already acknowledged that excessive motion after TDR might result in facet joint arthrosis and

hypertrophy, stenosis, and pain. This hypothesis seems to be partially proven when looking at the results of Punt et al. [14], who stated facet joint arthrosis as possible cause of failure after TDR. Recently, Siepe et al. [17] also reported of a substantial percentage of patients (33.1%) with significant pain after TDR. In 12.6% of their patients, the lumbar facet joints were diagnosed as the source of pain, mostly located at the index level. These findings are supported by a retrospective study of Shim et al. [15]. They compared the Prodisc and the Charité prostheses and found a progression rate of facet joint arthrosis in 32–36.4% of all patients. According to the authors, this high incidence of facet degeneration after an average follow-up of only 38–41 months cannot be explained by the natural course of degeneration. Having these facts in mind, it seems more than reasonable to look for factors influencing segmental mobility after TDR. At the best, such a factor should be influenceable by the surgeon through identified implant selection or surgical approach.

The reason for a hypermobility in case of reconstruction of the original disc space height, for flexion/extension and axial rotation, can be explained by the surgical approach as the anterior annulus fibers and anterior longitudinal ligament are resected during implantation and the lateral annulus fibers are preserved. The compensation for this “segmental ligamentous weakening” can only be achieved by distraction of the remaining segmental ligamentous elements.

With regard to the results of the current study, a segmental overdistracted of 2 mm, compared to the original disc space height, results in a compensation of the destabilizing effect of anterior annulus and PLL resection as the ROM values did not show any significant difference for flexion/extension and axial rotation compared to the intact specimen. However, the consequence of this overdistracted is a significant hypomobility in lateral bending. This might be the most striking and also disappointing observation of this study as none of the different implantation scenarios (with the prosthesis type used in the current

study) was able to reconstruct the intact ROM in all three principal motion planes.

Despite this, one should also keep in mind that the possible distraction of a disc space is limited for several reasons. Although the measurement of facet capsule tension and posterior muscle tension is not feasible nowadays, it is obvious that overdistraction of the disc space will also result in an overdistraction of these structures with possible negative side effects. Moreover, Liu et al. [8] reported about a significant decrease of the facet joint articulation overlap in sagittal plane following an increase in the lumbar disc space and mentioned that an inappropriate distraction will result in facet joint subluxation. Based on the observations of Liu et al. [8], it seems that overdistraction of the disc space might modify the biomechanics of the operated level, which potentially can result in a different load transfer at adjacent levels. Another consideration prohibiting excessive segmental distraction during implantation of a TDR is ligamentous failure. White already demonstrated that ligaments have a characteristic nonlinear load–displacement behavior which implies a violation of these structures in the so-called plastic zone [20]. This consideration seems of special interest as the current study was not a fatigue testing and that the removal of the PLL might be a reason for accelerated ligament loosening and muscle fatigue. The primary stability restoration with a higher implant might disappear after few weeks due to ligament and facet capsule loosening.

As the prosthesis type used in this study had a ball-and-socket principle, the results of the current study cannot be applied to an unconstrained prosthesis, such as, e.g., the Charité prosthesis, without reservation. Only one in vitro study by Weißkopf et al. [19] addressed this topic in case of the Charité prosthesis. After implantation of a proper sized Charité prosthesis in three cases (implantation level was not mentioned), no relevant difference of ROM for flexion/extension (increase of 0.3%) and lateral bending (increase of 3.2%) was observed compared to the intact specimen. As the disc space height before and after implantation was not measured in that study, no final conclusion can be drawn with regard to the influence of disc space height change after implantation on segmental ROM. Nevertheless, an obvious difference of the results can be noted as the ROM for flexion/extension increased by 26% and lateral bending decreased by 16% in the current study. Unfortunately, the results for axial rotation were not reported in the study by Weißkopf et al. [19] as in the current study the destabilizing effect of TDR implantation was most pronounced for axial rotation with an increase of 55% compared to intact specimen.

Based on the findings of the current study, possible recommendations for the implantation technique and

implant design of a constrained TDR with ball-and-socket principle might be:

1. If necessary, the PLL can be resected without creating a large segmental destabilization, as the increase was not more than 1° in median. But nevertheless one should keep in mind that the clinical consequences of this small destabilizing effect still remain unclear.
2. The reconstruction of the initial disc height would result in a destabilization especially in axial rotation.
3. Manufacturers should provide various TDR sizes, ideally with 1 mm steps in regard to the prosthesis height.

The results of the current study might result in the impression that increasing the prosthesis height might resolve possible problems of PLL resection, e.g., hypermobility. The authors of the current study explicitly do not promote bigger implant for stability as the possible negative consequences of disc space overdistraction are not conceivable. The impact of postoperative disc height changes on index level as well as adjacent level and surrounding structures (e.g., facet capsule, muscles, ligament) can only be evaluated in clinical studies. Therefore, the current study can only support and encourage further clinical research in this field, to clarify the real impact of PLL resection and disc space distraction on clinical results.

Limitations

A final recommendation with regard to the optimum postoperatively disc space height cannot be given with certainty as the effect of neither hypomobility nor hypermobility after TDR has been evaluated sufficiently at the moment and several other factors might also influence the postoperative resulting ROM after TDR, such as prosthesis type, number of implanted levels and also the postoperative pain level.

Conclusion

The resection of the PLL during TDR results in a significant increase of ROM in all three principle motion planes. However, it still remains unclear if an increase of not more than 1° may alter the clinical outcome. Moreover, the destabilizing effect of PLL resection can be reversed using a higher implant. The prosthesis height seems more crucial than PLL preservation to maintain the primary stability after TDR. Methods to preoperatively determine the ideal disc height, resulting postoperatively in a physiological ROM, seem not established yet.

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Conflict of interest statement None of the authors has any potential conflict of interest.

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