Dynamic stabilization adjacent to single-level fusion: Part I. Biomechanical effects on lumbar spinal motion

Patrick Strube · Stephan Tohtz · Eike Hoff ·
Christian Gross · Carsten Perka · Michael Putzier

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Abstract Progression of superior adjacent segment degeneration (PASD) could possibly be avoided by dynamic stabilization of an initially degenerated adjacent segment (AS). The current study evaluates ex vivo the biomechanics of a circumferential fixation connected to posterior dynamic stabilization at the AS. 6 human cadaver spines (L2–S1) were stabilized stepwise through the following conditions for comparison: intact spine (ISP), single-level fixation L5–S1 (SLF), SLF + dynamic AS fixation L4–L5 (DFT), and two-level fixation L4–S1 (TLF). For each condition, the moments required to reach the range of motion (ROM) of the intact whole spine segment under ± 10 Nm (WSP10) were compared for all major planes of motion within L2–S1. The ROM at segments L2/3, L3/4, and L4/5 when WSP10 was applied were also compared for each condition. The moments needed to maintain WSP10 increased with each stage of stabilization, from ISP to SLF to DFT to TLF ($p < 0.001$), in all planes of motion within L2–S1. The ROM increased in the same order at L3/4 (extension, flexion, and lateral bending) and L2/3 (all except right axial rotation, left lateral bending) during WSP10 application with 300 N axial preload ($p < 0.005$ in ANOVA). At L4/5, while applying WSP10, all planes of motion were affected by stepwise stabilization ($p < 0.001$): ROM increased from ISP to SLF and decreased from SLF to DFT to TLF (partially $p < 0.05$). The moments required to reach WSP10 increase dependent on the number of fixated levels and the fixation stiffness of the implants

used. Additional fixation shifts motion to the superior segment, according to fixation stiffness. Therefore, dynamic instrumentation cannot be recommended if prevention of hyper-mobility in the adjacent levels is the main target.

Keywords Biomechanical evaluation · Dynamic stabilization · Adjacent segment degeneration · Lumbar circumferential fusion · Segment instability · Low back pain

Introduction

Many studies report a clinically relevant and accelerated progression of degeneration in the vertebral disc adjacent to the fused level, making re-operation necessary [4, 16, 25, 27]. While some have proposed a genetic predisposition as a possible reason [13, 24], the problem described may be attributable to a compensatory increase in the range of motion in the adjacent segments. This increase can be even higher if an inter-vertebral cage is used for fusion [8, 11, 12, 17]. The disc superior to spondylodesis seems to be more heavily affected than the inferior [1]. Furthermore, adjacent disc degeneration was described more often when initial degeneration of the adjacent segment was present at the time of fusion surgery [9, 22]. Therefore, a prophylactic dynamic stabilization of a radiologically apparent, initially degenerated segment adjacent to fusion may be advantageous.

To avoid adjacent disc hyper-mobility and the possible resulting progression of degeneration, dynamic implants have been developed [10, 18, 32, 33]. Therapeutic strategy of these implants is stabilization by reducing loads while allowing motion in the treated segment. Besides the Graf ligaments, the Dynesys® implant is one of the longest known and applied dynamic implants [14, 33]. MRI and

P. Strube · S. Tohtz · E. Hoff · C. Gross · C. Perka ·
M. Putzier (✉)
Clinic for Orthopaedics, Center for Musculoskeletal Surgery,
Charité-Universitätsmedizin Berlin, Charitéplatz 1,
10117 Berlin, Germany
e-mail: michael.putzier@charite.de

cadaveric studies have shown that it preserves but limits motion in extension, flexion, and lateral bending, but does not completely compensate for increases in axial rotation compared to the intact spine [2, 31, 33]. It seems also to reduce facet joint loads and disc pressure in extension in the treated segment [28]. Despite a slight increase in motion and facet loads in the adjacent segment during rotation after implanting Dynesys®, it is able to reduce adjacent disc degeneration clinically [26].

To dynamically stabilize the segment adjacent to spondylodesis could decrease the rate of degeneration progression by reducing the hyper-mobility and facet joint loads resulting from fusion in the level inferior. To date, almost nothing is known about the biomechanical situation resulting from such instrumentation. Zander et al. [38] researched a hybrid construct with dynamic fixation in the segment inferior to single level fusion employing finite element model analysis. In a cadaveric study, Cheng et al. [3] compared intact and single-level destabilized spines to single-level and two-level instrumentation, as well as to two-level instrumentation with an intersomatic cage in the inferior segment. Instrumentation consisted of rigid internal fixation in the first and Dynesys® in the second group. A hybrid construct consisting of rigid fixation inferiorly and dynamic fixation superiorly was not applied in this study. They found no effect of single-level instrumentation on the adjacent level. Despite not investigating whole spine motion and the segment adjacent to the two-level instrumentation, they postulated that a dynamic stabilization in the adjacent segment might be advantageous in situations where excessive rigidity at the adjacent segment is neither desirable nor necessary.

Within the present cadaveric study, we aimed to evaluate lumbar spinal motion when fixated with a hybrid posterior implant. Motion analysis was performed in the dynamically stabilized (Dynesys®) adjacent segment superior to single level fixation and in the intact levels superior to dynamic instrumentation. Additionally, we compared the hybrid situation to single- and two-level fixation. The hypothesis was a limitation of motion in the Dynesys® level compared to a single-level fixation, while reducing the compensatory hyper-mobility of the whole lumbar spine—especially in the segments superior to the Dynesys® implant—compared to a two-level fixation.

Materials and methods

Specimen preparation

Six intact human cadaver spines (L2–S1) were employed for biomechanical testing (Table 1). Lateral and anterior–posterior X-rays of each specimen taken before the test did

Table 1 Donator data

Mean age at death (years)	60.8 (52–70)
Sex (f/m)	3/3
Mean body height (cm)	165.7 (150–181)
Mean body weight (kg)	70.7 (48–96)
Mean BMI (kg/m ²)	25.6 (18.9–30.6)

Values in parenthesis represent the ranges

not reveal any pathological conditions. According to the testing protocol of Wilke et al. [36], the soft tissue of the spines was dissected, while leaving capsules of the facet joints, supporting structures, and ligaments intact. Specimen ends were embedded in polymethyl methacrylate (Technovit® 3040, Heraeus Kulzer, Hanau, Germany) using custom-made casting containers, for mounting in the spine-testing device. The lumbar segment L3/4 was set to a horizontal position during the embedding procedure. The specimens were freshly frozen at –20°C in triple-sealed plastic bags, and were thawed to 20°C directly before embedding and biomechanical testing [31].

Spine tester

For biomechanical testing of the spines (Fig. 1), a spine tester was employed according the protocol of Wilke et al. [34]. The climate during testing was 20°C and 58% humidity. The spines were fixed rigidly at vertebra S1, while vertebra L2 was fixed with a gimbal allowing rotation in all three major planes of motion as well as vertical translation. A traveling gantry and a secondary slide enabled translation in the other two planes. Testing was performed according to the hybrid testing protocol recommended by Panjabi [21]—preserving the motion range of the intact spine while applying increasing moments—which is meant to reflect the moving strategy of treated patients. First, the whole intact spine segment L2–S1 was loaded with pure moments of ± 10 Nm. The whole spine segment L2–S1 range of motion (ROM) and mono-segmental ROM for segments L2/3, L3/4, L4/5, and L5/S1 were recorded, using a 3D optoelectric camera system (OptoTrak 3020, Northern Digital Inc., Waterloo, ON, Canada), in all three motion planes: flexion–extension, left–right lateral bending and left–right axial rotation. During all tests, moments were continuously applied at a rotation rate of 1.0°/s, and the specimens were allowed to move unconstrained in five degrees of freedom. For comparison between the testing conditions, the recorded whole spine segment ROM of the intact spine was applied to the surgically modified spine segments (L2–S1). The applied relative moments needed to reach the intact spine segment's ROM, as well as the segmental ROM for segments L2/3, L3/4, and L4/5 were measured for each condition.

Fig. 1 Picture of the biomechanical testing device with a specimen embedded

Segmental distribution of whole spine segment's ROM was recorded also for level L5/S1. For simulation of in vivo loads on the spine, all measurements were repeated under an axial compressive “follower” preload of 300 N, as recommended in the literature [23, 28, 29].

Testing conditions

On the day of thawing, directly before testing, titanium alloy pedicle screws (Allospine™, Zimmer, Winterthur, Switzerland) were bilaterally implanted in neutral position at vertebrae S1, L5, and L4 by an experienced spinal surgeon. Four testing conditions were created by varying the posterior instrumentation (Fig. 2): ISP (intact spine), SLF

(single-level fusion at level L5/S1), DFT (dynamically fixated at level L4/5, superior to rigid fixation of level L5/S1—Dynesys® Transition, Zimmer, Winterthur, Switzerland) and TLF (two-level fusion—L4–S1). The fusion conditions were simulated by dissecting the intervertebral disc, applying an anterior bone cement block and an anterior wire fixation between two vertebral body screws, and by posterior ane-stable transpedicular fixation using bilateral 6 mm rods. To bridge between the Dynesys® implant and rigid fixation, special connectors (Allospine™, Zimmer, Winterthur, Switzerland) were applied to the L5 pedicle screws (Fig. 2). Because testing was conducted below body temperature, the material of the Dynesys® spacer was modified to compensate for the resulting variation in material properties, as described by Schmoelz et al. [30]. The specimens were first tested in condition ISP followed by SLF, DFT, and TLF. Analysis was performed using data from the third loading cycle after two pre-cycles.

Statistical analysis

The statistical analyses were performed using the Prism 5.00 software (GraphPad Software Inc., San Diego, USA). To compare the four testing conditions in each plane of motion, a repeated-measure analysis of variance (ANOVA) with post-hoc Bonferroni testing was applied. *p* value was set to $p = 0.05$ in all tests.

Results

Subject matching was significant in all ANOVA testings performed ($p < 0.001$).

Moment measurements of the whole spine segment

In all planes of motion, an increase in the relative moment needed to reach the ROM of intact spine segment L2–S1

Fig. 2 Picture shows the posterior instrumentation of a cadaver spine segment in conditions SLF (L5–S1), DFT, and TLF (L4–S1) based on the Allospine™ [Dynesys® Transition (DFT)] device (Zimmer, Winterthur, Switzerland)

was recorded when the spine was instrumented. Mean moments increased in order of increasing fixation, from ISP to SLF to DFT to TLF, whether a preload was applied or not (Fig. 3a, b). The differences between the four testing conditions were significant in all planes of motion, with and without preload (ANOVA, each $p < 0.001$). Significance in post-hoc tests ($p < 0.05$) in the comparison of the conditions are indicated as brackets in Fig. 3. Segmental distribution of whole spine segments' ROM for all conditions with and without preload is presented in Figs. 4 and 5.

L2/3 ROM measurements

Results from the ROM measurements of L2/3 are presented in Table 2.

Without preload

Without applying preload, ROM testings of L2/3 revealed significant results in each major plane of motion (ANOVA:

right axial rotation $p = 0.046$; left lateral bending $p = 0.009$; each other $p < 0.001$). Mean ROM increased stepwise from ISP to SLF to DFT to TLF in all planes of motion except in extension and right axial rotation (mean ROM L2/3: ISP < DFT < SLF < TLF) as well as except in left lateral bending (mean ROM L2/3: ISP < SLF < TLF < DFT). Significance in post-hoc tests ($p < 0.05$) was found between ISP/SLF in extension, between ISP/DFT in left and right lateral bending, extension, and flexion as well as between SLF/TLF condition in flexion, left axial rotation, and right lateral bending. In each major plane of motion except left lateral bending, L2/3's mean ROM significantly increased (post-hoc tests $p < 0.05$) from ISP to TLF. The difference between DFT/TLF and between DFT/SLF was significant for flexion in post-hoc tests ($p < 0.05$).

With 300 N preload

With applying preload, ROM testings of L2/3 revealed significant results in each major plane of motion (ANOVA:

Fig. 3 Biomechanical test results of the whole spine segment's (L2–S1) moment measurements in percent of moments needed to preserve intact spine's ROM (at a load of ± 10 Nm). Brackets indicate

significant post-hoc test results between conditions ($p < 0.05$). Whiskers indicate single standard deviation. **a** With an axial preload of 300 N, **b** without an axial preload of 300 N

Fig. 4 Segmental relative distribution of whole spine segment's (L2–S1) ROM when preserving its intact ROM (at a load of ± 10 Nm; with an axial preload of 300 N) in conditions intact spine (*ISP*), single level fusion (*SLF*), dynamic fixation transition (*DFT*), and two level fusion (*TLF*). Results are demonstrated in percent of total ROM for **a** flexion, **b** extension, **c** axial rotation (left and right presented together), and **d** lateral bending (left and right presented together). *Whiskers* indicate single standard deviation

Fig. 5 Segmental relative distribution of whole spine segment's (L2–S1) ROM when preserving its intact ROM (at a load of ± 10 Nm; without an axial preload of 300 N) in conditions intact spine (*ISP*), single level fusion (*SLF*), dynamic fixation transition (*DFT*), and two level fusion (*TLF*). Results are demonstrated in percent of total ROM for **a** flexion, **b** extension, **c** axial rotation (left and right presented together), and **d** lateral bending (left and right presented together). *Whiskers* indicate single standard deviation

each $p < 0.001$) except in right axial rotation ($p = 0.083$). Therefore, no post-hoc tests were performed for right axial rotation. Changes between conditions are demonstrated in Table 2. Significance in post-hoc tests ($p < 0.05$) was found in extension (ISP vs. all other conditions; SLF/DFT; SLF/TLF), flexion (ISP/DFT; ISP/TLF; SLF/TLF), left axial rotation (TLF vs. all other conditions), left (ISP/DFT; ISP/TLF), and right lateral bending (SLF/TLF; ISP/DFT; ISP/TLF).

L3/4 ROM measurements

Results from the ROM measurements of L3/4 are presented in Table 3.

Without preload

Without applying preload, measurements of axial rotation and extension of L3/4 did not reveal any significant

Table 2 ROM L2/3 when preserving ROM of intact spine segment L2–S1

Degree of freedom	Preload (N)	Intact spine ^a	Single level fusion ^a	Dynamically fixated transition ^a	Two level fusion ^a
Extension	0	−2.04 ± 0.74	−3.15 ± 1.27	−2.93 ± 0.75	−3.50 ± 1.15
	300	−1.52 ± 0.90	−2.33 ± 0.80	−2.83 ± 0.94	−3.27 ± 1.15
Flexion	0	3.34 ± 1.99	3.49 ± 1.53	4.79 ± 1.97	5.40 ± 2.19
	300	3.26 ± 1.53	3.92 ± 1.89	5.03 ± 2.63	5.46 ± 2.69
Lateral	0	−3.80 ± 1.66	−4.26 ± 1.89	−5.18 ± 2.01	−4.78 ± 2.17
Bending left	300	−3.24 ± 1.49	−3.91 ± 1.73	−4.73 ± 1.65	−4.69 ± 1.51
Lateral	0	3.30 ± 1.17	4.37 ± 1.49	5.34 ± 1.66	5.51 ± 1.67
Bending right	300	3.15 ± 1.42	3.84 ± 1.80	4.63 ± 1.64	4.77 ± 1.65
Axial	0	−1.51 ± 1.14	−2.01 ± 1.84	−1.79 ± 1.19	−2.25 ± 1.13
Rotation right	300	−1.22 ± 0.82	−1.54 ± 1.28	−1.38 ± 0.73	−1.79 ± 0.74
Axial	0	1.29 ± 0.50	1.47 ± 0.70	1.76 ± 1.01	2.35 ± 0.86
Rotation left	300	1.23 ± 0.71	1.25 ± 0.61	1.36 ± 0.62	1.79 ± 0.68

^a Values reported in mean ± single standard deviation (°); (*n* = 6)

Table 3 ROM L3/4 when preserving ROM of intact spine segment L2–S1

Degree of freedom	Preload (N)	Intact spine ^a	Single level fusion ^a	Dynamically fixated transition ^a	Two level fusion ^a
Extension	0	−2.03 ± 0.98	−2.14 ± 1.35	−2.69 ± 1.15	−2.57 ± 0.78
	300	−2.33 ± 1.05	−2.89 ± 1.30	−3.62 ± 1.88	−3.66 ± 1.69
Flexion	0	3.51 ± 1.93	4.00 ± 1.61	5.14 ± 1.64	5.07 ± 1.40
	300	2.26 ± 1.26	3.02 ± 0.99	4.02 ± 0.96	3.97 ± 1.07
Lateral	0	−3.43 ± 1.28	−3.90 ± 1.01	−4.55 ± 1.01	−4.81 ± 1.20
Bending left	300	−2.58 ± 1.27	−2.77 ± 1.01	−3.34 ± 0.70	−3.47 ± 1.04
Lateral	0	4.10 ± 1.16	4.24 ± 1.40	5.65 ± 1.70	5.74 ± 1.96
Bending right	300	2.49 ± 1.30	2.71 ± 0.92	3.40 ± 0.68	3.53 ± 1.01
Axial	0	−2.50 ± 1.27	−2.42 ± 1.01	−2.95 ± 1.35	−3.11 ± 1.34
Rotation right	300	−1.85 ± 0.78	−1.80 ± 0.63	−2.23 ± 0.93	−2.25 ± 0.94
Axial	0	2.26 ± 1.37	2.81 ± 1.34	2.55 ± 0.93	2.48 ± 1.09
Rotation left	300	1.74 ± 0.73	2.16 ± 0.89	2.19 ± 0.89	2.14 ± 0.83

^a Values reported in mean ± single standard deviation (°); (*n* = 6)

difference between the conditions in post-hoc tests, despite a significant ANOVA result in right axial rotation ($p = 0.029$). In flexion and lateral bending (each ANOVA $p < 0.001$), we observed an increase in L3/4 ROM when a fixation system was applied to the spine segment. Mean ROM increased in the order of stepwise fixation (although without increase from DFT to TLF in flexion). In the post-hoc tests, this difference was significant for both ISP and SLF compared to all other conditions ($p < 0.05$) in flexion and right lateral bending. In left lateral bending, the difference between ISP and bi-segmentally instrumented conditions (DFT, TLF) and between SLF/TLF, was statistically significant (post-hoc tests $p < 0.05$).

With 300 N preload

When bi-segmentally instrumented, right axial rotation measurements showed an increase in mean ROM compared to SLF and ISP (non-significant in all post-hoc tests;

ANOVA $p = 0.023$). Left axial rotation revealed a significant increase in mean L3/4 ROM, when any fixation was applied, compared to the intact spine (ANOVA $p = 0.005$). In extension, flexion (each ANOVA $p < 0.001$) and lateral bending (ANOVA left $p = 0.002$ and right $p = 0.001$), the mean ROM increased in the order of fixation stages, from ISP to TLF (but no increase from DFT to TLF in flexion). Significance in post-hoc tests ($p < 0.05$) were found in extension and flexion (ISP/DFT, ISP/TLF), left axial rotation (ISP vs. all other conditions), as well as in left and right lateral bending (ISP/DFT, ISP/TLF, SLF/TLF).

L4/5 ROM measurements

Results from the ROM measurements of L4/5 are presented in Table 4. All ANOVA tests on level L4/5 ROM showed statistically significant relationships (each $p < 0.001$). In all measurements of level L4/5, with and without preload, a

Table 4 ROM L4/5 when preserving ROM of intact spine segment L2–S1

Degree of freedom	Preload (N)	Intact spine ^a	Single level fusion ^a	Dynamically fixated transition ^a	Two level fusion ^a
Extension	0	-2.07 ± 0.74	-2.41 ± 0.95	-1.66 ± 1.50	-0.33 ± 0.19
	300	-1.85 ± 0.61	-2.56 ± 0.94	-0.82 ± 0.47	-0.15 ± 0.11
Flexion	0	4.16 ± 2.57	4.68 ± 2.27	0.57 ± 0.28	0.14 ± 0.11
	300	2.31 ± 1.15	3.12 ± 1.50	0.58 ± 0.29	0.02 ± 0.07
Lateral Bending left	0	-3.03 ± 1.01	-3.46 ± 1.27	-0.62 ± 0.35	-0.27 ± 0.22
	300	-1.96 ± 1.28	-2.17 ± 1.42	-0.50 ± 0.38	-0.05 ± 0.08
Lateral Bending right	0	3.33 ± 1.42	3.55 ± 1.71	0.42 ± 0.24	0.17 ± 0.10
	300	1.71 ± 0.94	2.18 ± 1.23	0.46 ± 0.33	0.04 ± 0.03
Axial Rotation right	0	-2.32 ± 0.78	-2.53 ± 0.75	-1.47 ± 0.34	-0.38 ± 0.26
	300	-1.89 ± 0.59	-1.99 ± 0.76	-1.36 ± 0.33	-0.28 ± 0.17
Axial Rotation left	0	2.10 ± 0.71	2.17 ± 1.09	1.46 ± 0.46	0.67 ± 0.35
	300	1.76 ± 0.39	1.93 ± 0.47	1.27 ± 0.37	0.39 ± 0.20

^a Values reported in mean $\pm$ single standard deviation ($^{\circ}$); ($n = 6$)

non-significant increase in mean ROM was observed from ISP to SLF. Additionally, the mean ROM decreased in the order of stepwise fixation, from SLF to DFT to TLF, in each plane of motion.

Without preload

The decrease in the mean ROM from DFT to TLF was significant (post-hoc tests $p < 0.05$) with respect to right axial rotation and extension. Mean ROM measurements revealed significant differences (post-hoc tests $p < 0.05$) between SLF/DFT and ISP/DFT, for right axial rotation, flexion, and left and right lateral bending. There was a statistically significant difference (post-hoc tests $p < 0.05$) in the mean ROM between conditions TLF/SLF and between TLF/ISP in all planes of motion.

With 300 N preload

Significance in post-hoc tests ($p < 0.05$) were found in extension and flexion (ISP/DFT, ISP/TLF, SLF/DFT, SLF/TLF), left axial rotation (TLF vs. all other conditions; SLF/DFT), right axial rotation (TLF vs. all other conditions), as well as in left and right lateral bending (ISP/DFT, ISP/TLF, SLF/TLF, SLF/DFT).

Discussion

To the authors' knowledge, this is the first in vitro biomechanical evaluation of the effects of a dynamically fixated spinal level adjacent to a rigid single-level lumbar fixation (hybrid instrumentation). It is also the first comparison between such instrumentation and intact spine, and single- or two-level rigid fixation, and its effects on the

dynamically fixated level and the adjacent superior level. Within this evaluation, increasing stiffness of the fixation implant and increasing number of treated levels led to elevated moments required to reach the intact spine's ROM. Depending on the implant stiffness, we showed that two-level instrumentation leads to an increased ROM in the segments adjacent to the instrumentation by protectively reducing the ROM in the superior instrumented level.

As with other in vitro biomechanical studies, results of the present work have to be carefully interpreted, since they were conducted in an idealized spine testing apparatus, where muscle forces are difficult to mimic [31]. To date, there is no definitive method reported for testing the effects of spinal instrumentation in vitro. We followed the hybrid testing protocol of Panjabi, who suggested measuring the ROM of intact spines while applying pure moments and preserving this ROM during implant tests by applying higher moments and measuring the resulting segmental ROM changes [21]. One disadvantage of this method is that with repeated application of increasing moments (in this study up to 35 Nm) the specimens can structurally be damaged and implants can show loosening. However, neither implant loosening nor macroscopic implant damage could be observed during the testing. Nevertheless, a negative influence on the results cannot be completely excluded. Another disadvantage of the method is the dependence of the ROM measurements on the length of the whole tested spine segment. In case of testing a longer segment, the increase of ROM in the adjacent segments will be distributed to more than two or three adjacent segments and therefore be lower. However, this method is thought to reflect the relevant situation in which a patient would try to preserve their non-instrumented level of mobility by compensatory increases in muscle force and motion in the adjacent segments. The hyper-mobility of

adjacent segments observed in patients after spinal fusion supports this hypothesis. Schmoelz et al. [31] tested adjacent level effects by applying pure moments of ± 10 Nm and measuring the resulting ROM of the segments, as recommended by Wilke et al. [35]. They were not able to show an effect of single-level fixation on the adjacent segment, but they also stated that reality may lie between the two models. Applying Schmoelz's test method in our experimental setup resulted in an outcome similar to that of Schmoelz et al. (data not shown).

We observed that implanting a rigid fixation device in a single level made increasing relative moments necessary to reach the intact spine's mobility in each plane of motion (except for right lateral bending with preload, and both sides without preload). The addition of fixation devices to the level adjacent to fusion led to a further increase of these moments (rigid > dynamic fixation). The moments were elevated even under axial preload. This leads to two conclusions: first, that by absorbing loads, dynamic fixation produces a protective and stabilizing effect; second, that patients would have to apply much greater muscle forces to preserve preoperative motion status after such surgery. The differences between Dynesys[®] Transition and two-level fixation were predominantly observed in axial rotation and extension. Apart from these planes of motion, the stabilizing effects of the Dynesys[®] implant seem to be close to that of rigid internal fixation. This observation is comparable to the results of a previous biomechanical study [31].

The segmental ROM measurements revealed only very small influence of single-level fixation on the ROM of the three superior adjacent segments (significant increase in left axial rotation at level L3/4 with preload applied and in extension at level L2/3). Especially no significant influence was found on the directly adjacent segment (L4/5). These results contrast with in vitro and in vivo studies, where a hyper-mobility was observed after single-level fusion [5–7]. DFT led to a decrease of the ROM of L4/5 segment in all planes of motion, except for axial rotation compared to the intact condition; when compared to single-level fixation of L5/S1, axial rotation was also decreased. Thereby, the slight (but not significant) hyper-mobility of level L4/5 after single-level fusion can be compensated, although excessively, by applying Dynesys[®] at the level adjacent to fusion. Considering the hypothetical instability of a slightly degenerated adjacent segment, this overcompensation could be beneficial. Beastall et al. [2] demonstrated a similar effect of Dynesys[®] in a destabilized segment by functional MRI measurements in vivo. A two-level fixation reduced the overall ROM of L4/5 compared to the intact segment and single-level fixation. Compared to the DFT-condition, a further decrease in the ROM of L4/5 in axial rotation and extension was observed when two level were rigidly fixed. These results support the outcome of the

whole spine segment moment measurements and highlight the differences between the Dynesys[®] implant and rigid fixation with respect to axial rotation and extension [31].

Both dynamic and rigid fixation of L4/5, adjacent to rigid fixation of L5/S1, led to an increase of the mean ROM at L3/4 in extension, flexion, lateral bending and left axial rotation and at L2/3 in all major planes of motion except axial rotation compared to the intact spine. Compared to single level fixation, bi-segmental instrumentation (dynamic and rigid) led to a further increase of the mean ROM of L3/4 for flexion and right lateral bending, whereas axial rotation and extension of L3/4 seemed not to be significantly affected by the additional fixation at L4/5 superior to rigid fixation. Therefore, hyper-mobility of the adjacent levels increased with the number of fixated levels. Hyper-mobility of segments adjacent to rigid fixation was also observed in previous studies [5–7]. Again, the effects of the Dynesys[®] implant seem to be very close to those of rigid fixation, since there were no significant differences at L3/4 between DFT and TLF conditions in any plane of motion. However, considering all planes of motion, the mean increase in L3/4 ROM from SLF to TLF condition was higher than the mean increase from single-level fusion to dynamic fixation. This increase became significant between SLF and TLF but not between SLF and DFT regarding L3/4's lateral bending. Therefore, we suggest a small protective effect of dynamic fixation of L4/5 on L3/4's lateral bending compared to a TLF-condition.

At L2/3, a significant increase of the mean ROM in TLF compared to SLF condition was observed in all planes of motion except left lateral bending and right axial rotation. However, L2/3's mean ROM in DFT condition was largest for left lateral bending and it was smaller than in SLF and TLF conditions in extension (without preload) and right axial rotation. Nevertheless, L2/3's ROM in DFT condition was always very close to that in TLF condition except for (left) axial rotation (with preload) and flexion (without preload). Surprisingly, there we found a significant difference between DFT and TLF in these planes of motion. Therefore, there might be an additional protective effect of dynamic fixation on the more superior adjacent segment for axial rotation and flexion.

The observed inconsistency of the results for left and right lateral bending or axial rotation may be explained by the small sample size of the study, by differences during the implantation procedure or by anatomical variance of the spine specimens. Dynesys[®] implant's stiffness was shown to be dependent on the PCU spacer length, which is dependent on the distance between the pedicle screws at each side [20]. This could possibly result in a side-specific variation of implant stiffness. A variety of new dynamic implants have been developed without this variability in implant stiffness and may be part of future studies [15, 37,

39]. First, new implants will require specific evaluations of their biomechanical behavior as well as clinical trials for safety and outcomes.

The results of this study only reflect the effect of the implants on the intact—and not surgically destabilized—spine. The aim was to test the effects of dynamic stabilization for the indication of an existing initial degeneration in the segment adjacent to fusion. When restoring the motion of a destabilized spine to values close to that of the intact spine, the protective effects on the adjacent segment may be greater with Dynesys® or another dynamic stabilization implant than with a two-level fusion.

In previous studies, spinal testing has been conducted with no preload or with axial preloads of up to 1,200 N [23, 29]. To allow for this inconsistency, we tested all conditions both without and with a preload of 300 N to simulate muscular stabilizing effects. Considering the results of this study, we cannot indicate a preference for either testing condition. Both situations led to similar—but differing in detail—results. Therefore, we suggest performing tests in both situations.

Effects on intradiscal pressure and facet joint loads have also been described as being influenced by axial preload and spinal implants itself [19, 28, 30, 38], but were not studied in our experiments. Therefore, a conclusion regarding these parameters cannot be made.

In conclusion, we demonstrated that whenever a fixation device is added to the lumbar spine, the moments needed to reach the intact spine's ROM increase depending on the number of fixated levels and the fixation stiffness of the implants used. With an increasing number of fixated levels and increasing stiffness of the fixation device, the adjacent segments show an increasing compensatory hyper-mobility, which could either cause or possibly accelerate adjacent segment degeneration. Adding Dynesys® adjacent to a single-level fusion can protect the adjacent level from hyper-mobility by load-sharing and limiting ROM of this instrumented level. This protective limitation of ROM is close to that of a two-level fusion, except in extension and axial rotation. The Dynesys® implant also leads to hyper-mobility of the segments adjacent to dynamic fixation, possibly resulting in a progression of degeneration of these segments. However, a small benefit might exist for lateral bending at the segment adjacent to dynamic fixation as well as for axial rotation and flexion in the more superior adjacent segment when employing Dynesys® Transition instead of a two-level fusion. In general, a transition fixation could be advantageous in clinical cases with a slight degeneration and instability of segment directly adjacent to single-level fusion, but cannot be recommended if prevention of hyper-mobility in the more superior adjacent levels is the main target.

Conflict of interest None.

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