Total disc arthroplasty: consequences for sagittal balance and lumbar spine movement

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Abstract This in vivo biomechanical study was undertaken to analyze the consequences for sagittal balance and lumbar spine movement in three different lumbar disc prostheses. A total of 105 patients underwent total disc replacement in three different centers. The Maverick[®] prosthesis was used in 46 patients, the SB Charité[®] device was used in 49 patients and the Prodisc[®] device was utilized in 10 patients. The analysis was computer assisted, using Spineview[®] and Matlab[®] softwares. The intra and inter-observer reliability and measurement uncertainty was performed. The analysis of lateral X-ray films in flexion–extension allowed to measure the prosthesis positioning, the range of motion (ROM), the localization of the mean center of rotation (MCR), the vertebral translation and the disc height, for each prosthesis device. The sagittal balance was analyzed on a full spine film. The parameters studied were described by Duval-Beaupère. The results were compared to the data found in literature, and compared to 18 asymptomatic volunteers, and 61

asymptomatic subjects, concerning the sagittal balance. The prostheses allowed an improvement of the ROM of less than 2°. The ROM of L5–S1 prostheses ranged from 11.6 to 15.6% of the total lumbar motion during flexion–extension. At L4–L5 level, the ROM decreased when there was an arthrodesis associated at the L5–S1 level. There was no difference of ROM between the three prostheses devices. The MCR was linked to the ROM, but did not depend on the prosthesis offcentering. The disc height improved for any prosthesis, and decreased in flexion or in extension, when the prosthesis was offcentered. An increase of translation indicated a minor increase of the ROM at L4–L5 level after Maverick[®] or SB Charité[®] implantation. The L5–S1 arthrodesis was linked with an increase of the pelvic tilt. The lumbar lordosis curvature increased between L4 and S1, even more when a prosthesis was placed at the L3–L4 level. Total disc arthroplasty is useful in the surgical management of discogenic spinal pathology. The three prostheses studied allowed to rerotate the disc height, the ROM, without disrupting the sagittal balance, but induced modification of the lumbar curvature.

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Introduction

Managing patients with lumbar disc degeneration is still a challenge, particularly for young adults. A discectomy for nucleus herniation and a disc degenerative disease may be responsible of a loss of discal height,

then of static and kinematics changes. Patients present with low back pain or leg pain.

Spinal fusion has remained the most common treatment of disabling mechanical low back pain. It restores the disc height, but it induces degenerative lesions of the adjacent intervertebral discs [9, 12, 14]. Many studies report encouraging clinical outcomes after total disc replacement: limitation of blood loss during operation, significant improvement in Oswestry scale and in VAS scale, return to full-time employment [1, 2, 5, 8, 11, 18, 19, 27]. Few studies investigated the biomechanical point of view of total disc prosthesis *in vivo*; among nine articles concerning the total disc replacement, only four measured the prosthesis mobility. The operated segment does appear to move with a reported average ROM of 5 to 12° [3, 5, 6, 16, 27]. None of them measured the positioning of the center of intervertebral rotation described by Percy [20], except Cunningham in cadaveric lumbar spines [4]. In this study, the total disc replacement versus conventional methods of stabilization preserves the segmental kinematics and centropdes of intervertebral motion at the operative and adjacent spinal levels. To our knowledge, the sagittal balance of the spine has never been studied after total disc replacement.

In the present retrospective study, our aims were to analyze the biomechanical consequences of a total disc replacement at lumbar level in a sample of subjects with various prosthesis for (1) kinematics, concerning the ROM and the position of the MCR, and (2) sagittal balance.

Materials and methods

Study population

Our sample is divided into four sub-samples:

- The first group includes 46 patients recruited for a prospective study on the Maverick® total disc arthroplasty system [13] (Medtronic Sofamor Danek, Memphis, USA), between October 2002 and November 2003. The surgical procedures were made by a single surgeon in Bordeaux, following the description of Mayer [18].
- The second group includes 49 patients, operated by a single surgeon using an SB Charite III® prosthesis [16] in Dijon, France. It was divided into two sub-groups, according to the follow-up of more than 11 years or less than 1 year.

- The third group includes 10 patients, operated by a single surgeon using a Prodisc® prosthesis [18, 27], in Marseille, France.
- A fourth group is a control group: the sagittal balance was studied in 61 asymptomatic subjects, and the lumbar kinematics was assessed in 18 volunteers.

The demographic characteristics and prosthesis localization are described in Table 1. We defined as “simple” a single-level prosthesis without arthrodesis and any adjacent level pathology, and as “complex” a prosthesis multiple or associated with an arthrodesis or any adjacent level pathology.

The inclusion and exclusion criteria were the criteria to receive a lumbar disc prosthesis [19].

Data collection

Preoperative and postoperative radiographic pictures at the longest follow-up were collected. It consisted of a lateral view of the flexion and extension of the lumbar spine, standing antero-posterior, and lateral full spine film (including the femoral heads). These X-ray films were digitalized using Vidar System Corporation® VXR12+ and analyzed using Spineview® software (Surgiview corporation, Paris, France), developed in collaboration between the team of LIO CHUM Montreal and LBM ENSAM CNRS UMR 8005 in Paris. The various measurements were processed by pointing the corners of the vertebral bodies, the femoral heads, and the auditory canal. An automatic detection was processed to highlight the contours of each vertebra which were then manually better defined. The reliability of the Spineview® software has already been studied in previous work [17].

Sagittal balance assessment

The implantation of a total disc arthroplasty can induce changes in the global equilibrium. In order to measure these changes, the spine balance and the pelvic orientation were assessed in the sagittal plane. Seven parameters studied for the sagittal balance evaluation were determined from previous studies, such as sacral tilt (ST), pelvic tilt (PT), pelvic incidence (PI), global lordosis, global kyphosis, T9 sagittal tilt [15]. Spine global inclination was also studied. The spine global inclination is the angle between the vertical line and the line passing at best by the centroids of the body of the vertebrae in the direction of the lesser squares [24]. The values were compared to those of asymptomatic volunteers [10, 15, 22].

Table 1 Demographic characteristics of the sample and the control group

	<i>N</i>	Sex (males in %)	Follow-up (month): mean (range)	Age mean (range)
Total sample	105	37.6	31.2 (3–168)	43 (28–58)
Bordeaux (Maverick [®])	46	40.9	7.5 (3–15)	46.8 (35–58)
Dijon 1 (SB charite III [®])	16	50	14.1 (120–168)	39.3 (29–56)
Dijon 2 (SB Charite III [®])	33	25	11.3 (4–28)	39.4 (29–56)
Marseille (Prodisc [®])	10	40	8.7 (3–40)	44 (38–54)
Control group for sagittal balance	61	42.6		43 (31–55)
Control group for kinematics	18	39		35 (26–51)

Kinematics assessment

The parameters studied for kinematics assessment were the following: segmental lumbar spine angle, position of the MCR, intervertebral translation, disc height [24]. The MCR is localized thanks its co-ordinates. *X* is expressed as a percentage of the length of the vertebral end plate, and *Y* as a percentage of the height of the posterior wall. The MCR position was not localized when the ROM was less than 3°. The usual location of the MCR is in a circle, whose center is placed between 30 and 50% of the superior vertebral endplate, and whose diameter is 70% of the vertebral endplate size [21]. The translation is expressed in percentage of the vertebral endplate, and the disc height expressed in percentage of the size of the posterior vertebral cortex.

A single observer measured the parameters. Repetition of the measurements of the MCR was performed 20 times in one patient to assess the intraobserver reliability. The same measurements were performed by an other experimental observer, allowing to investigate the interobserver reliability.

Prosthesis position assessment

The prosthesis position was analyzed in frontal and sagittal plane, using a specific program. On the lateral view, the anterior and posterior corners of the superior and inferior vertebral endplates and prosthesis components were marked out. On the frontal view, the corners of the vertebral endplates, the center of the pedicles, the spinous process and the lateral sides of the prosthesis and its fins were also marked out. The sagittal prosthesis positioning was analyzed on the lateral X-ray view. The studied parameters were:

- Angle between each prosthesis and its vertebral endplate.
- Size of the prosthesis compared to the size of the vertebral endplate (in percentage). We considered a priori as a normal prosthesis size between 60 and 90% of the vertebral endplate size.

- The prosthesis positioning was compared to the center of the vertebral endplate. The measurement is the distance between the center of the prosthesis and the center of the vertebral endplate, compared to the size of the endplate (in percentage). The prosthesis was considered in a centered position, when the ratio was less than 10%.

The frontal position of the prosthesis was analyzed on the antero-posterior X-ray view. The studied parameters were:

- Vertebral rotation on the frontal view is evaluated by comparing the distance between the spinous process and each pedicle center. If the ratio was between 0.8 and 1.2, we considered that the vertebral body had a minimal axial rotation on the antero-posterior X-ray view. In the other case, the frontal position was not taken into account.
- Angle between each prosthesis component and its vertebral endplate
- Prosthesis off centering: we measured the distance between the center of the vertebral endplate and the center of the prosthesis, compared to the endplate size. A ratio of more than 10% was considered as an offcentering in the frontal plane.

Statistical analysis

Data were collected using an Excel[®] table, and the statistical analysis was performed using Stata 7[®] software [23]. We used univariate analysis (Student *t* test and chi square test) and non-parametric test (Wilcoxon–Mann–Whitney test) to compare sub-groups. Inter- and intra-observer reliabilities were assessed by calculating the standard deviation of the various measurements using Statview[®] software. After checking that the differences are normally distributed, we considered that the mean uncertainty measurement was equal to two standard deviations.

Results

Sample description

Ninety-six percent of the prostheses were placed at L5–S1 and L4–L5 level. Only one subject had more than 3 prostheses. Details are available in Table 2.

Percentages are given only for subjects for whom information was available. Prosthetic size and positioning are detailed in Table 3. In sagittal plane, 105 (93%) of total prostheses have a superior component size equal to 60 to 90% of the superior vertebral endplate. The mean prosthetic size of the sample is 80.6% of the vertebral endplate. Twenty-four out of 46 lumbar spine X-ray was not in a strict antero-posterior direction, if we take into account the predefined criteria. The subsidence of any component of the prosthesis is not significantly associated with the prosthesis size (Mann–Whitney test, $P = 1$).

Measurement reliability

The intraobserver ROM uncertainty depends on the lumbar level. The mean uncertainty measurement is 2.4° at L5–S1 level, 2.3° at L4–L5 level, 2.0° at L3–L4 and L2–L3 level, and 2.2° at L1–L2 level. The interobserver

ROM reliability was the same, except at the L4–L5 level (2.4°).

The mean intraobserver uncertainty of the MCR is 26% for X value and 32% for Y value at L5–S1 level. It is between 8 and 14% from L4–L5 to L2–L3 levels, and reaches 24% for Y value at L1–L2 level. The mean of MCR interobserver uncertainty is 28 and 34% for X and Y values at L5–S1 level, is between 10 and 18% at L4–L5 to L3–L2, and is 14 and 24% for X and Y values at L1–L2 level.

Description of kinematics and sagittal balance in total sample and control group

Kinematics analysis in total sample

Lumbar spine range of motion (Table 4) The improvement in segmental ROM at any prosthesis level is less than 2° . The average part of mobility due to single level L5–S1 prosthesis ranges from 11.6 to 15.6% of total lumbar ROM. The percentage of ROM due to L4–L5 prostheses reaches 22.9%. The mobility of L4–L5 prosthesis decreases when combined with an arthrodesis. No significantly different ROM was found after disc replacement for any type of single-level prostheses. There is no significant difference of ROM

Table 2 Distribution of the prostheses in the samples, according to their level of implantation and number of multilevel implantations

	Total sample, $N = 106$	Bordeaux (Maverick®), $N = 57$	Dijon (SB charite®), $N = 63$	Marseille (Prodisc®), $N = 10$
L5–S1	41	17	18	6
L4–L5	41	23	14	4
L3–L4	3	3	1	
2 prostheses implanted	18	2	16	
3 prostheses implanted	1		1	
Prosthesis + arthrodesis	15	12	3	

Table 3 Prosthesis size and positioning in simple cases

	Total sample, $N = 82$	Maverick®, $N = 43$	SB Charité®, $N = 29$	Prodisc®, $N = 10$
Prosthetic size ^a				
Sagittal	81.3 (65.6–102.1)	81.8 (65.6–102.1)	80.3 (70.4–92.7)	81.7 (72.4–89.1)
Frontal	82 (65.6–80)	81.8 (65.6–103.1)		86.2 (83.3–89.1°)
Prosthetic offcentering ^b				
Sagittal	5.3 (0.2–16.5)	6 (0.3–16.5)	4.7 (0.2–15.7)	4 (0.4–9.9)
Frontal	5.8 (0.3–5.7)	6.1 (0.3–16.5)		0.7 (0.4–1)
Prosthetic subsidence ^c				
Sagittal	5.1 (0.1–17.1)	5.2 (0.1–17.1)	5 (1–10.5)	4.7 (1.4–9.9)
Frontal	5.2 (0–17.1)	5.2 (0.1–17.1)		5.4 (1.6–9.2)

^a Expressed in percentage of the size of the vertebral endplate

^b Percentage of the vertebral endplate; 0% offcentering means centered

^c In degrees, compared to the vertebral endplate

Table 4 Segmental ROM at the prosthesis level, before and after total disc replacement. Part of the prosthesis motion in total lumbar spine ROM

	ROM at the prosthesis level in degrees (min; max)		Segmental ROM compared to L1–S1 ROM (in %)	
	Before	After	Before	After
“Simple” L5–S1 prosthesis				
Maverick®	6.1 (–2.9; 22.3)	5 (–4.6; 22.3)	13.4	12
SB Charité®	5.4 (–3; 14.7)	7.2 (–0.8; 14.7)	11.6	15.6
Prodisc®	8.2 (–6.7; 18.6)	12.6 (3.2; 17.4)	28.2	25.6
Control group	9.4 (–3.3; 18.7)		17.5	
“Simple” L4–L5 prosthesis				
Maverick®	7.4 (–6.4; 19.7)	8.1 (–2.3; 21.1)	22.3	22
SB Charité®	11.1 (1.4 ; 18.9)	10 (1.2 ; 18.9)	26.2	22.9
Prodisc®	12.2 (0.8; 20.2)	8.5 (–2.7; 13.1)	31.1	15.2
Control group	14.5 (6.5; 23.5)		27	
“Simple” L3–L4 prosthesis				
Maverick®	14.4 (13.6; 15.3)	10 (1.9; 15.3)	28.6	
Control group	11.2 (5.2; 16.8)		20.6	
L4–L5 prosthesis + arthrodesis				
Maverick®	7.5 (–6.4; 19.7)	5.8 (1.9–12.2)	27.5	17.6
SB Charité® ^a	14.8 ^a	7.2 ^a		
Control group	14.5 (6.5; 23.5)		27	

^a One subject available

between Maverick and SB Charite prostheses at L4–L5 level (Mann–Whitney test: $z = 0.7$, $P = 0.5$) and at L5–S1 level (Mann–Whitney test: $z = 1.7$, $P = 0.08$). At these levels, the ROM are not significantly linked with the number of prostheses of the lumbar spine (Mann–Whitney test, $P = 0.8$ and $P = 0.4$).

Mean center of rotation (Table 5) The number of MCR localized in the “usual area” does not increase thanks to Maverick device at any level. The SB-Charité prosthesis seems to relocalize the MCR in the normal position at any level.

The prosthesis MCR is significantly associated with the ROM at L5–S1 level [9.6° (5.6) versus 4.1° (4.4), Mann–Whitney test: $P = 0.0004$], at L4–L5 level [10.4° (4.3) versus 7.8° (5.5), Mann–Whitney test: $P = 0.002$]. At L3–L4 level, the ROM tends to be higher when MCR is in the usual area compared to the unusual area. Prosthetic sagittal offcentering (>10%) does not influence neither L5–S1 ROM (Mann–Whitney test: $P = 0.6$), nor L4–L5 ROM (Mann–Whitney test: $P = 0.8$).

There is no significant link between MCR localization and frontal and sagittal offcentering (t test: $t = 0.5$, $P = 0.6$, $df = 85$) and antero-posterior subsidence (t test: $t = 1.5$, $df = 85$, $P = 0.13$), among single prostheses and in total sample.

Intervertebral disc height and intervertebral translation (Tables 6 and 7) In the total sample, the prosthesis increases the disc height. At L5–S1 level, the posterior disc height decreases from 44.2 to 35% of the vertebral height when the prosthetic excentration is more than 10% in the sagittal plane.

The intervertebral translation is studied in the sagittal plane, at the prosthetic level. There is a significant increase of intervertebral translation during flexion–extension at L4–L5 level after total disc arthroplasty, but not at L5–S1 level. At L4–L5 level, the range of translation is significantly higher for the SB Charité® device compared to Maverick® in extension (Mann–Whitney test: $P = 0.0006$) and in flexion (Mann–Whitney test: $P = 0.0001$). At L5–S1 level, the range of translation is not significantly different for the SB Charité® device compared to Maverick. The translation at L3–L4 level seems to have decreased.

Sagittal balance analysis

Pelvic incidence (PI) The mean pelvic incidence is not different before [49.7° (SD 9.8)] and after disc replacement [49.1° (SD 9.7)]. It is neither different from the control group mean value. In all cases, the PI value is in the normal range.

Pelvic tilt (PT) The mean pelvic tilt is not significantly different before and after disc replacement [14° (SD 7) vs. 12.6° (SD 8); paired t test: $t = 0.6$, $P = 0.5$, $n = 45$]. In the total sample, more than 89% of the patients were in the normal range before and after total disc replacement. In 20 patients having an L5–S1 prosthesis, the pelvic tilt was 11.7° (SD 8.1) before surgery, and 9.1° (SD 6.9) after total disc arthroplasty, tending to an improvement. The PT is not different before and after total disc replacement at L4–L5 and

Table 5 Prosthesis MCR localization before and after total disc replacement

	L5–S1 prosthesis N (%)		L4–L5 prosthesis N (%)		L3–L4 prosthesis N (%)	
	Before	After	Before	After	Before	After
Bordeaux sample (Maverick [®])						
Normal	2 (29)	4 (23.5)	9 (64)	14 (61)	2 (100)	1 (33)
Anterior	1	2	2	1	0	0
Posterior	1	1	1	2	0	0
Others	2	10	2	6	0	2
Dijon sample (SB Charité [®])						
Normal	3 (27)	9 (50)	9 (64)	11 (78.5)		
Anterior	1	0	0	0		
Posterior	0	1	1	1		
Others	7	3	2	2		
Marseille sample (Prodisc [®])						
Normal	3 (50)	3 (50)	3 (75)	3 (75)		
Anterior	0	0	0	0		
Posterior	1	0	0	1		
Others	2	3	1	0		

Table 6 Disc height and intervertebral translation before and after disc replacement in flexion and extension, at the level of prosthesis implantation

	Measurement position	Before disc replacement, mean (SD)	After disc replacement, mean (SD)	Statistical test ^a , paired <i>t</i> test, <i>df</i> , <i>P</i>
L5–S1 prosthesis				
Anterior disc height ^b	Flexion	38.8 (7.9)	55.8 (12.1)	
	Extension	47.3 (18.4)	67.6 (12.7)	
Posterior disc height ^b	Flexion	28.9 (14)	58.1 (15.9)	
	Extension	21.8 (9.3)	45.8 (12.8)	
Intervetebal translation ^c	Flexion	3.8 (2.1)	4.2 (9.3)	<i>t</i> = 0.7, <i>P</i> = 0.5
	Extension	4.7 (7.5)	4.8 (6.6)	<i>t</i> = 0.9, <i>P</i> = 0.2
L4–L5 prosthesis				
Anterior disc height ^b	Flexion	43.8 (34.3)	49.3 (10.8)	<i>t</i> = 0.8, <i>P</i> = 0.4
	Extension	56.3 (36.6)	61.9 (10)	<i>t</i> = 0.7, <i>P</i> = 0.5
Posterior disc height ^b	Flexion	37.2 (12.1)	47.6 (12.7)	<i>t</i> = 3.3, <i>P</i> = 0.002
	Extension	31.7 (17.2)	41.2 (11.5)	<i>t</i> = 2.5, <i>P</i> = 0.02
Intervetebal translation ^c	Flexion	5.8 (4.7)	7.9 (5.9)	<i>t</i> = 2.3, <i>P</i> = 0.02
	Extension	8.7 (4.2)	10.8 (6.8)	<i>t</i> = 2, <i>P</i> = 0.05
L3–L4 prosthesis				
Anterior disc height ^c	Flexion	37.8 (5.4)	44.3 (9.1)	
	Extension	57 (9.8)	67.2 (12.4)	
Posterior disc height ^c	Flexion	48.3 (1.2)	41.1 (0.8)	
	Extension	31.2 (2.2)	34.4 (0.8)	
Intervetebal translation ^c	Flexion	8 (1.3)	5.7 (0.2)	
	Extension	12.2 (0.1)	10.4 (1.2)	

^a Paired *t* test was performed only if the group includes at least 30 subjects^b Disc height is a percentage of the size of the vertebral body^c Intervertebral translation is expressed in percentage of the size of the vertebral endplate

L3–L4 level. The L5–S1 arthrodesis seems to improve pelvic tilt after L4–L5 total disc replacement: the PT improves from 16.1° (SD 6) to 14.1° (SD 8.8) without arthrodesis versus 14.3° (SD 5.9) to 15.8° (SD 6.9) with L5–S1 arthrodesis. The PT values remain in normal range. The PT is neither influenced by sagittal excen-

tration [5.3 (SD 3.2) vs. 5.4 (SD 3.9)] nor subsidence [4.7 (SD 3.8) vs. 5.8 (SD 3.9)].

Sacral slope (SS) Nearly 92% of the patients had a normal SS before surgery with a mean of 35.9° (SD 6.2), and 94.2% have a normal slope after disc

Table 7 Range of intervertebral translation in sagittal plane, according to the type of prosthesis and the level of implantation

	Measurement position	Maverick [®] , mean (SD)	SB Charite [®] , mean (SD)	Prodisc [®] , mean (SD)
L5–S1 prosthesis	<i>N</i>	16	33	5
	Flexion	5.9 (7.4)	5.1 (8.5)	0.6 (6.8)
	Extension	6.4 (5.8)	5.8 (7.4)	4 (10.4)
L4–L5 prosthesis	<i>N</i>	23	30	4
	Flexion	3.8 (4.2)	10.4 (4.8)	7.7 (6.9)
	Extension	7.4 (4.1)	12.8 (6.1)	11.8 (3.5)
L3–L4 prosthesis	<i>N</i>	3	2	0
	Flexion	7.2 (2.5)	13.4 (3.3)	
	Extension	9.2 (2.3)	14.9 (5.1)	

Intervertebral translation is expressed in percentage of the size of the vertebral endplate

N number of cases available

replacement with a mean of 36.3° (SD 5.8). The mean SS improves by about 1° after L5–S1 prosthesis (35.4° to 36.3°) and L4–L5 prosthesis (36.2° to 37.4). After L3–L4 prosthesis, the mean Sacral Slope is 30.6° (SD 6.1), compared to 25.3° (SD 1) before operation, but it concerned only three subjects. The L5–S1 arthrodesis associated with a L4–L5 prosthesis does not significantly influence the SS modification before and after surgery; all SS values remain in normal range [37.8 (SD 7.1) to 38.1 (SD 8.8) in 29 subjects without arthrodesis vs. 33.3 (SD 9.3) to 35.4 (SD 6.7) in 10 subjects with arthrodesis].

Lumbar lordosis (LL) (Table 8) The mean lumbar lordosis in the total sample is significantly higher after total disc replacement [50.3 (SD 9.8) to 52.4 (SD 9.9); paired *t* test: *t* = 2, *P* = 0.05]. The increase of L1–S1 lordosis is neither linked with an increased angle at the prosthesis level, nor with an increased ROM at the

prosthesis level. Sixty-three subjects (94%) have a postoperative LL in the physiological range. The mean postoperative total LL is not different if the prosthetic level is L5–S1 or L4–L5. After L3–L4 prosthesis, the mean lumbar lordosis is smaller, but two out of three subjects have a LL in the normal range. Arthrodesis at L5–S1 level, tends to modify the lumbar lordosis, compared to subjects without arthrodesis [47.3 (SD 11) vs. 53.3 (SD 9.7)]. The L1–S1 lordosis is not associated neither with the sagittal prosthesis excentration, nor with prosthesis size. The lumbar curvature depends on the prosthesis level: L4–S1 curvature represents 93% of the total Lumbar lordosis after L3–L4 prosthesis, and 73% of the total LL after L4–L5 and L5–S1 prostheses.

Association of pelvic parameters (pelvic incidence, pelvic tilt, sacral slope and lumbar lordosis) were tested in pairs, using chi square tests. The PT and PI ($\chi^2 = 3.6$, *df* = 1, *P* = 0.06), PT and SS ($\chi^2 = 3.6$, *df* = 1,

Table 8 Measurement of total and segmental lumbar lordosis according to prosthetic type, prosthetic level and after L5–S1 arthrodesis

	Total lumbar lordosis (L1–S1) (degrees), before and after disc replacement		Value of the segmental Lumbar lordosis between two vertebrae (in degrees) mean (SD), % of total lumbar lordosis			
	Before	After	L5–S1	L4–S1	L3–S1	L2–S1
Total sample	50.3 (9.8)	52.4 (9.9)	21.7 (6.5), 41.2%	36.5 (7.2), 70.5%	46 (7.8), 90%	51.1 (8.7), 98.6%
According to prosthetic type						
Maverick	50.3 (10.3)	52 (10.6)	21.1 (7), 40.5%	35.3 (7.4), 63.3%	45.5 (8.5), 87.3%	51.2 (9.5), 98.2%
SB Charite		47.2 (9.9)	22.6 (6.4), 47.9%	39.1 (7.5), 82.8%	46.3 (7.3), 98%	48.5° (7.7), 102.7%
Prodisc	53.4 (8.4)	58 (4.2)	23.2 (3.4), 40%	37.5 (4.5), 64.6%	48.8 (4.2), 84%	55.2 (4.1), 95%
According to prosthetic level						
L5–S1		52.2 (8.9)	23 (5.7), 44%	38 (6.2), 72.8%	47.5 (6), 91%	52 (7.2), 99.6%
L4–L5		50.9 (11.2)	20.8 (6.8), 40.8%	35.3 (7.8), 69.7%	44.6 (8.4), 87.6%	50 (9.6), 98.2%
L3–L4		42.8 (13.5)	24.7 (10.4), 57%	39.9 (10), 93.2%	47.1 (15.3), 110%	45.4 (14), 106%
With L5–S1 arthrodesis		45.5 (10.6)	21.1 (8.2), 46%	33.9 (9.6), 74.4%	43.2 (10.5), 94.9%	46.6 (10.3), 102%

$P = 0.06$), LL and SS ($\chi^2 = 7.1$, $df = 1$, $P = 0.008$) are significantly associated.

Thoracic kyphosis The mean T4–T12 thoracic kyphosis is 37° (SD 8.8) before surgery, and 36.7° (SD 10.7) after total disc arthroplasty. The difference is not significant (paired t test $n = 46$, $t = 1.1$, $P = 0.27$). There is no statistical link between lumbar lordosis and thoracic kyphosis ($\chi^2 = 0.94$, $df = 1$, $P = 0.33$).

T9 sagittal tilt The T9 sagittal tilt was -10° before and after surgery. It is significantly linked with the L1–S1 lumbar lordosis ($\chi^2 = 3.9$, $df = 1$, $P = 0.048$).

Discussion

Methodological limitations

Subject recruitment was not randomized. It was based on each surgeon's recruitment, but inclusion and non-inclusion criteria, the mean age and the sex ratio of the subjects were the same for each group. Moreover, our sample comprises three sub-samples of small size. It limits the analyses and the interpretations of the study findings. So, we often gave only descriptive data in tables. The follow-up of 2 years is perhaps too short to evaluate the risk of subsidence of the prosthesis device that increases with time.

The use of a vertical digitalizer avoids picture distortion. In our study, the largest measurement uncertainty concerns the sacral slope (2.4°), as described in literature [25, 26]. In many cases, the sacral endplate is not flat, but in the shape of dome; the definition of the antero-superior angle is difficult and could explain the uncertainty measurement. The first 50 measurements, corresponding to the software learning curve, were not taken into account to minimize the uncertainty measurements.

Interpretation of findings

General findings

Disc height In our study, at L4–L5 and partially at L5–S1 level, the prosthesis significantly increased the discal height, as described in former studies [16]. Particularly, when the sagittal offcentering is more than 10% ahead, the center of rotation is localized ahead, and the disc height in extension is significantly reduced. It can explain the persistent radicular and zygapophyseal joint pain in such a situation.

ROM So far, there is no significant association between the prosthetic positioning in the sagittal plane

and the ROM at the prosthesis level. The ROM of L5–S1, L4–L5, and L3–L4 single-level prostheses is not significantly different after total disc replacement in pre- and postoperative period. It corresponds to the systematic review of 564 prostheses [6]. We found no significant difference of L4–L5 and L5–S1 ROM for the Maverick® and the SB Charite® prosthesis. It would mean that a semi-constrained total disc arthroplasty like Maverick® and Prodisc® prostheses allow the same ROM as a non-constrained prosthesis (SB Charité®), at L5–S1 level, in our study.

Sagittal balance In our sample, more than 90% of the pelvic and spinal parameters were in the normal range before and after total disc replacement [7]. We have shown that the patient undergoing a disc replacement prosthesis is able to maintain the global preoperative sagittal balance parameters including lordosis, sacral tilt, and pelvic tilt. The level and the ROM of the prosthesis induces no significant changes of the value of L1–S1 lumbar spine lordosis. But, L1–S1 lumbar lordosis value decreases when the prosthesis is located at L4–L5 and even more when the prosthesis is localized at L3–L4 level. After a total disc replacement, as described in asymptomatic subjects, the segmental contribution to the lordotic curve increases distally, and when a prosthesis is placed at L3–L4 level, the L4–S1 segmental lumbar lordosis represents more than 90% of the lumbar curve. This result is based on six subjects. It seems that L3–L4 prostheses create important changes in the lumbar curvature.

MCR

The clinical relevance of the MCR was highlighted by Pearcy [20]. Since, it provides complementary information of the spine kinematics, the location of the MCR was found in the usual area at the adjacent level to the prosthesis. This was also generally the case at the instrumented level. The graphic representation of the MCR at the prosthetic level highlights that an unusual location of the MCR is associated with a prosthetic excenteration or may be linked to a conflict induced by the bone formation which modifies the flexion–extension motion (Fig. 1). There is no significant link between the location of the MCR and the prosthesis offcentering, its size or its subsidence on the sagittal plane. But if we analyze each MCR prosthesis that is not in the usual area, we find each time an explanation: the prosthesis may be offcentered, or there is a bone formation that shifts the MCR. It seems that the statistical analysis has not allowed to highlight these

Fig. 1 MCR localization and prosthetic positioning **Fig. 2** MCR positioning in 18 asymptomatic subjects

particular cases. The MCR in the control group was found in agreement with previous studies [4, 20]. The representation of the position of the MCR in a control group (Fig. 2), shows that at L5–S1 level, the location of the MCR is more posterior, but not in a well defined fixed position. At the upper levels, the MCR is located in a fixed position. It would mean that the total disc

arthroplasties are more adapted for an implantation at L4–L5 level than at L5–S1 level.

The uncertainty measure of the MCR in intra- and inter-observer study rises to 34% of the vertebral endplate's size at L5–S1 level. The location of the MCR depends on the coordinates of the corner of the vertebral body in flexion and extension. As the

sacral endplate has a dome shape, the software had trouble in identifying the corners of S1 endplate. The MCR was located but with a high degree of uncertainty.

Prosthesis size and positioning

In the present study, we decided a priori the normal size of a prosthesis on the sagittal plane. There is no norm, and to our knowledge, we found no significant correlation between prosthesis size and any assessed item of functioning. The “normal” positioning of the prosthesis on the sagittal view was also a priori determined as centered. The choice of these criteria is questionable: the kinematics at the two last levels is different and could require a different positioning of the prostheses. The prosthetic subsidence was small, and had no significant influence on the ROM and even on the location of MCR. This could be due to the short follow-up of our study.

Conclusion

Our study analyzed the consequences on the lumbar spine motion of three various total disc arthroplasties. This computer-assisted analysis has allowed to assess many biomechanical parameters of the lumbar spine during flexion and extension motion, and classic parameters of the sagittal balance. The total disc arthroplasty did not improve the segmental ROM, but increased the disc height, except if the prosthesis was offcentered on the sagittal plane. The posterior longitudinal ligament release during surgery is not measurable on X-ray, and seems to be a very important point to increase the flexion–extension ROM. The L4–L5 level seems to have a more simple biomechanical functioning and seems to be more adapted to receive a total disc prosthesis. After total disc arthroplasty, patients were able to maintain their preoperative sagittal balance. We found no important differences between the three prostheses devices, except in translation above L5–S1 level.

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