C. Knop
U. Lange
L. Bastian
M. Blauth

Three-dimensional motion analysis with Synex

Comparative biomechanical test series with a new vertebral body replacement for the thoracolumbar spine

Received: 25 January 2000
Revised: 5 May 2000
Accepted: 22 May 2000

Abstract The authors present a new implant for vertebral body replacement in the thoracic and lumbar spine. Synex is a titanium implant designated for reconstruction of the anterior column in injury, post-traumatic kyphosis or tumour of the thoracolumbar spine and must be supplemented by a stabilizing implant. After positioning, the implant is distracted in situ, thus ensuring best contact with adjacent end-plates and three-dimensional (3D) stability, and minimizing the possibility of secondary dislocation or loss of correction. We compared the effectiveness of the Synex implant with that of the “Harms cage” (MOSS) in combination with two alternative stabilizing instrumentations: the USS and Ventrofix. In a 3D spinal loading simulator, we determined the bisegmental (T12–L2) neutral zone (NZ), elastic zone (EZ), and range of motion (ROM) of 12 human cadaveric spines. After corpectomy of L1, we tested the four possible combinations of stabilizing instrumentation and vertebral replacement implant: USS/Synex, USS/MOSS, Ventrofix/Synex, Ventrofix/MOSS. We analysed the differences between each of the instrumentations as well as differences compared to the intact spine. Comparing the two stabilizing implants, a significantly higher stability was achieved with the USS for

flexion, extension, and lateral bending, regardless of whether Synex or MOSS was used as vertebral body replacement. No differences were observed for axial rotation. In addition, no implant combination was able to restore the rotational stability of the intact spine. Comparing the vertebral body replacing implants, significantly higher stability was noted with Synex in combination with USS for extension, lateral bending, and axial rotation. No differences between Synex and MOSS were observed in combination with Ventrofix. Posterior fixation was found to offer superior stability compared to anterior fixation. Synex was at least comparable to MOSS for suspensory replacement of the vertebral body in the thoracolumbar spine. The increased biomechanical stability demonstrated for Synex suggests that a more rigid construction would also be achieved in vivo. When using MOSS in combination with posterior stabilization, the induction of intervertebral compression via the posterior fixator is recommended. This surgical step was not necessary with Synex.

Key words Thoracolumbar spine · Biomechanics · Stability · Vertebral body replacement · Spinal fixation · Titanium implant · Harms cage · Synex

This project was financially supported by STRATEC Medical, Oberdorf, Switzerland

C. Knop (✉) · U. Lange · L. Bastian
M. Blauth
Department of Trauma Surgery,
Hannover Medical School,
Carl-Neuberg-Straße 1,
30625 Hannover, Germany
e-mail: Dr.Christian.Knop@T-Online.de,
Tel.: +49-511-5322026,
Fax: +49-511-5325877

Introduction

In unstable injuries of the thoracolumbar spine, posterior stabilization with an angularly stable internal fixator has proved the standard procedure [35, 36]. Disagreement currently exists as to the best method for restoring normal load-bearing of the anterior spine and achieving intervertebral fusion. Arguments in favour of a purely posterior procedure are that it achieves stabilization by transpedicular means with less invasive access and the fact that the anterior column can also be reached. Although transpedicular cancellous bone grafting has been described as one way of achieving intervertebral fusion [13, 14, 15, 22, 43, 44, 51, 66], recent reports suggest that this technique is associated with a considerable loss of correction and that the aim of anterior fusion cannot reliably be achieved [33, 34, 55, 67].

In cases involving considerable traumatic destruction of the anterior column, in the form of a complete or incomplete burst fracture according to the Magerl classification [45], or in cases of post-traumatic kyphosis or tumours of the vertebral body, many authors prefer an anterior or combined postero-anterior procedure for restoring normal load-bearing in a biomechanically and clinically stable spine [4, 5, 6, 7, 8, 9, 12, 18, 32, 33, 34, 38, 46, 56, 62, 64, 65, 73]. However, this approach has its own drawbacks: the more complex surgical technique is associated with significantly longer operating times and increased blood loss [16, 25, 36]. Several authors have also observed increased morbidity and complications as a result of strut graft harvesting from the iliac crest [2, 23, 38, 42, 59, 63, 71, 72]. Complications specific to the procedure itself have also been reported, e.g. pseudarthrosis or fracture of the strut graft [21, 32, 39]. There are still no long-term results confirming the superiority of this method in a direct comparison that could justify the extra effort involved [7, 9].

Synex (STRATEC Medical, Oberdorf, Switzerland) is a new implant for vertebral body replacement (Fig. 1), designed to avoid the disadvantages of graft harvesting from the iliac crest and, at the same time, restore normal load-bearing in the anterior spine [37]. The range of indications for the implant include all lesions of the thoracolumbar spine involving considerable destruction of the vertebral bodies and reduction of the axial load-bearing capacity of the anterior spine. These include, on the one hand, traumatic lesions involving an incomplete or complete burst fracture according to the Magerl classification [45] and, on the other, post-traumatic kyphosis and tumours of the thoracolumbar spine.

Synex is to be used together with a stabilizing implant to produce a solid construction with rigid tensioning of the vertebrae covered by the spondylodesis. The risks of a secondary dislocation or loss of correction are to be minimized. Compression tests with isolated human vertebral body specimens (L1) showed that sinking into the vertebral end-plate was significantly reduced with Synex compared to MOSS, resulting in significantly greater compressive force at the interface between implant and vertebral body [37].

Objectives

In the present biomechanical test series we wanted to test the bisegmental stability after corpectomy of L1 with subsequent stabilization and vertebral body replacement. The bisegmental motion of the intact spine in the three directions was compared with that of the instrumented spine. The following questions were to be answered:

1. What differences are apparent between the various implant combinations compared to the intact spine?

Fig. 1 Synex and MOSS implants for vertebral body replacement

2. Is there any difference between postero-anterior stabilization with the USS (Synthes Medizinaltechnik GmbH, Bochum, Germany) and the purely anterior approach with Ventrofix (Synthes Medizinaltechnik GmbH, Bochum, Germany)?
3. Does vertebral body replacement with Synex differ from that with MOSS in combination with the combined and anterior approaches?

Materials and methods

We used exclusively freshly harvested specimens of human spines of T10–L4 with no macroscopically visible major degenerative or pathological changes. The average height and weight of the donors were 172 cm (range 163–186 cm) and 79 kg (range 67–103 kg), respectively. After removal, the specimens were freed of adjoining muscles, sealed in plastic bags, and frozen to -18°C . The test conditions formulated by Wilke et al. [70] were observed during storage as well as during handling of the specimens in the preparatory and test phases. The cortical and trabecular bone mineral densities (BMD_{cort} , BMD_{trab}) of the spines were determined in a water bath by dual-energy quantitative computed tomography (DE-QCT) (Somatom plus S; Siemens, Munich-Erlangen, Germany), using OsteoCT software and a reference phantom [19, 28, 29, 30, 47, 57, 58, 60]. Bone density was expressed in milligrams of calcium hydroxyapatite per unit of volume. The mean density was 99.2 mg/cm^3 (range $64.6\text{--}162.5 \text{ mg/cm}^3$) for BMD_{trab} and 248.8 mg/cm^3 (range $161.5\text{--}323.1 \text{ mg/cm}^3$) for BMD_{cort} .

We used a loading simulator in which the clamped specimens could be loaded with infinitely variable pure moments in three di-

Fig. 2 Loading simulator with mounted specimen

Fig. 3 Intact specimen mounted on the simulator (the arrows indicate sensors for the electromagnetic object tracking system, secured via extensions in T12 and L1)

rections of motion (Fig. 2) with reference to the coordinate system described by White and Panjabi [68]. The system was operated by a stepping motor, and the movement deflections recorded by an object tracking system based on low-frequency magnetic field technology (Motion tracker, 3Space Fastrak; Polhemus, Colchester, Vermont, USA) (Fig. 3). The measuring accuracy given by the manufacturer involves an error level of 0.1° and 0.1 mm . Preliminary trials with a variety of instrumentation set-ups showed an additional error of 2%.

Vertebrae T10/T11 were secured cranially and L3/L4 caudally in the simulator's retaining units. We fixed the sensors in vertebral bodies T12 and L2 for the bisegmental measurement of motion. After calibrating the system, we first determined the motion of the intact specimen. Following a complete corpectomy of L1, including the adjacent disks, the specimens were stabilized bisegmentally with Ventrofix (Ventrofix double-rod system, titanium) or USS (Fracture system, 6-mm Schanz screws, 1 cross-linking element, titanium). After preparation of the end-plates, the L1 vertebral body was replaced by MOSS (size 3, $22 \times 28 \text{ mm}$, internal stabilization ring secured by screws on both sides, titanium) or Synex (end-plate size $25 \times 28 \text{ mm}$, height $31\text{--}46 \text{ mm}$, end-plate angle of inclination 0° , blue, titanium) (Fig. 4, Fig. 5):

MOSS was cut to the correct length and placed between both end-plates, such that the implant was aligned with the centre of the vertebral bodies in the sagittal and frontal planes. In a third surgical step, we induced intervertebral compression on the "Harms cage" by "tensioning" via the stabilizing implant, as described for the situation in vivo [62, 65].

Synex was inserted into the spinal implant site in its shortest, non-distracted state and adjusted for correct fit. Synex is distracted in the intervertebral position to the desired height with a special "spreader forceps". The self-locking "ratchet mechanism" maintains the height of the implant and prevents any slippage. Therefore, no additional "tensioning" via the stabilizing implant was necessary.

The four possible implant combinations were employed in each specimen in a random sequence according to a randomization list:

Combined postero-anterior instrumentation (group C; $n = 24$): USS + Synex ($n = 12$); USS + MOSS ($n = 12$)

Anterior instrumentation (group A; $n = 24$): Ventrofix + Synex ($n = 12$); Ventrofix + MOSS ($n = 12$)

Fig. 4 After corpectomy of L1 and stabilization with USS, Synex is distracted in its intervertebral position using the spreader forceps

Fig. 5 Specimen mounted on the simulator with implant combination of Ventrofix and MOSS

To create a comparable baseline situation with uniform pre-tensioning of the cables for all specimens, we used a preload of 0.5 Nm. After calibration of the motion measuring system, the specimens were loaded with pure moments at a constant rate of increase of 0.3 Nm/s up to 7.5 Nm [70], and the load was then reduced to the initial level. Three loading and unloading cycles were performed, and we calculated the range of motion (ROM) as the movement between the initial value and the maximum value for the third movement cycle, the elastic zone (EZ) between the minimum and maximum values for the third movement cycle and the neutral zone (NZ) between the minimum for the third movement cycle and the initial value [52, 53, 70]. The range of motion thus corresponded to the sum of the neutral and elastic zones.

After testing for normal distribution by the Kolmogorov-Smirnov method, with significance correction according to Lilliefors, we were able to assume normal distribution for the above-mentioned parameters, and used the *t*-test for paired samples for the comparison between the two implant combinations and the comparison with the intact spine. In the comparison between the combined and anterior groups ($n = 24$), we checked the results for significant differences using the *t*-test for independent samples.

Results

Flexion

In terms of flexion, bisegmental motion was at its lowest with the postero-anterior stabilization with USS (group C), regardless of the type of vertebral body replacement, with a mean range of motion of 1.2° (Fig. 6, Table 1). The average ROM measured for the intact specimen was 5.6°, compared to 6.7° after anterior stabilization (group A). NZ, EZ and ROM were thus reduced by a factor of about 5 in group C compared with group A (for NZ, EZ, ROM, $P < 0.001$) and by a factor of about 4 compared with the intact spine (for NZ $P = 0.009$; for EZ, ROM $P < 0.001$). The EZ and the ROM in group A were roughly similar to those of the intact specimen (NS), while the NZ was twice as large ($P < 0.001$).

Fig. 6 Neutral zone (NZ), elastic zone (EZ) and range of motion (ROM) for flexion of the intact specimen and the four implant combinations: USS/Synex (US), USS/MOSS (UM), Ventrofix/Synex (VS), and Ventrofix/MOSS (VM) (NZ + EZ = ROM; error bar shows standard deviation of ROM)

Table 1 Bisegmental motion for flexion (in degrees): mean $\pm$ SD values for neutral zone (NZ), elastic zone (EZ) and range of motion (ROM), and *P*-values for statistical comparison^a

	Intact specimen	Combined postero-anterior instrumentation Group C		Anterior instrumentation Group A	
		USS Synex	USS MOSS	Ventrofix Synex	Ventrofix MOSS
NZ (°)	1.46 ± 0.97	0.48 ± 0.21	0.65 ± 0.31	3.18 ± 1.77	3.95 ± 1.77
Comparison to intact specimen: P_{NZ}		0.009	0.014	0.006	0.001
Comparison of Synex and MOSS: P_{NZ}		0.062		0.104	
NZ (°)		0.57 ± 0.27		3.56 ± 1.78	
Comparison to intact specimen: P_{NZ}		0.009		<0.001	
Comparison of groups C and A: P_{NZ}		<0.001			
EZ (°)	4.16 ± 1.83	0.58 ± 0.15	0.69 ± 0.31	3.39 ± 1.72	2.84 ± 1.24
Comparison to intact specimen: P_{EZ}		<0.001	<0.001	0.145	0.027
Comparison of Synex and MOSS: P_{EZ}		0.211		0.064	
EZ (°)		0.63 ± 0.25		3.12 ± 1.49	
Comparison to intact specimen: P_{EZ}		<0.001		0.076	
Comparison of groups C and A: P_{EZ}		<0.001			
ROM (°)	5.62 ± 1.92	1.06 ± 0.34	1.34 ± 0.56	6.57 ± 3.37	6.79 ± 2.93
Comparison to intact specimen: P_{ROM}		<0.001	<0.001	0.284	0.213
Comparison of Synex and MOSS: P_{ROM}		0.066		0.737	
ROM (°)		1.20 ± 0.47		6.68 ± 3.09	
Comparison to intact specimen: P_{ROM}		<0.001		0.285	
Comparison of groups C and A: P_{ROM}		<0.001			

^a *t*-test, paired samples: individual comparison of the four different preparation states with the intact specimen (*first row*) and comparison between Synex and MOSS within groups C and A (*second*

row); *t*-test, independent samples: individual comparison between groups C and A and the intact specimen (*third row*) and comparison between groups C and A (*fourth row*)

No significant differences were observed in group C.

Extension

The comparison for extension showed no significant difference between the combined stabilization group (ROM = 4.7°) and the intact specimen (ROM = 4.4°) (Fig. 7, Table 2). Group A showed the same ROM as the intact specimen (4.8°), but a significantly greater NZ ($P = 0.002$) and lower EZ ($P < 0.001$). The same applies to the comparison between the anterior stabilization (group A) and the combined stabilization (group C): with the same ROM ($P = 0.875$), a significantly higher NZ ($P < 0.001$) and significantly lower EZ ($P < 0.001$) were apparent in the A group.

The smallest range of motion, 3.4°, was measured for the combination USS/Synex, without significant difference to the intact spine. The difference compared to the combination USS/MOSS (ROM = 6°) was significant (for NZ $P = 0.035$; for EZ, ROM $P < 0.001$).

In the A group, the construction with Synex (ROM = 4.2°) tended to be more stable than that with MOSS (ROM = 5.3°), with a significant difference in EZ (for NZ $P = 0.149$; for EZ $P = 0.008$; for ROM $P = 0.079$).

Fig. 7 NZ, EZ, and ROM for extension of the intact specimen and the four implant combinations

Lateral bending

The ROM measured for lateral bending with the four implant combinations (Fig. 8, Table 3) was between 3.5° (USS/Synex) and 4.2° (Ventrofix/MOSS). All constructions were thus more stable in this respect than the intact specimens (ROM = 5.3°). A significant difference was observed in group C (for EZ, ROM $P < 0.001$).

Table 2 Bisegmental motion (NZ, EZ, ROM) for extension (in degrees), and *P*-values for statistical comparison^a

	Intact specimen	Combined postero-anterior instrumentation Group C		Anterior instrumentation Group A	
		USS Synex	USS MOSS	Ventrofix Synex	Ventrofix MOSS
NZ (°)	1.20 ± 0.74	0.69 ± 0.35	1.22 ± 0.75	2.67 ± 1.05	3.46 ± 2.44
Comparison to intact specimen: P_{NZ}		0.082	0.949	0.001	0.006
Comparison of Synex and MOSS: P_{NZ}		0.035		0.149	
NZ (°)		0.95 ± 0.63		3.06 ± 1.88	
Comparison to intact specimen: P_{NZ}		0.305		0.002	
Comparison of groups C and A: P_{NZ}				<0.001	
EZ (°)	3.24 ± 1.04	2.66 ± 1.03	4.77 ± 0.81	1.56 ± 0.50	1.83 ± 0.69
Comparison to intact specimen: P_{EZ}		0.178	0.006	0.001	0.004
Comparison of Synex and MOSS: P_{EZ}		<0.001		0.008	
EZ (°)		3.71 ± 1.41		1.70 ± 0.60	
Comparison to intact specimen: P_{EZ}		0.313		<0.001	
Comparison of groups C and A: P_{EZ}				<0.001	
ROM (°)	4.44 ± 1.33	3.35 ± 1.06	5.98 ± 1.05	4.23 ± 1.44	5.29 ± 2.83
Comparison to intact specimen: P_{ROM}		0.072	0.008	0.649	0.279
Comparison of Synex and MOSS: P_{ROM}		<0.001		0.079	
ROM (°)		4.67 ± 1.69		4.76 ± 2.27	
Comparison to intact specimen: P_{ROM}		0.690		0.659	
Comparison of groups C and A: P_{ROM}				0.875	

^a *t*-test, paired samples: individual comparison of the four different preparation states with the intact specimen (*first row*) and comparison between Synex and MOSS within groups C and A (*second*

row); *t*-test, independent samples: individual comparison between groups C and A and the intact specimen (*third row*) and comparison between groups C and A (*fourth row*)

Fig. 8 NZ, EZ, and ROM for lateral bending (mean value of motion to the left and right) of the intact specimen and the four implant combinations

The comparison between Synex and MOSS in group C showed an identical NZ ($P = 0.212$) and a significantly lower EZ (difference = 0.2° ; $P = 0.02$) and ROM (difference = 0.3° ; $P = 0.021$). No significant differences were apparent between the vertebral body replacements (for NZ $P = 0.319$; for EZ $P = 0.275$; for ROM $P = 0.257$).

The left and right lateral bending showed identical values for NZ, EZ and ROM for the intact specimens and af-

ter stabilization with USS (group C). After stabilization with Ventrofix (group A), the comparison between sides showed significantly lower values for EZ (-1.1° ; $P < 0.001$) and ROM (-1.6° ; $P = 0.002$) in lateral bending toward the right.

Rotation

In terms of rotation (Fig. 9, Table 4), the intact spine was significantly more stable (ROM = 2.1° ; $P < 0.001$) than the four implant combinations, whose ROM ranged from 6.6° (Ventrofix/Synex) to 8.9° (USS/MOSS). The NZ measured for the four stabilized specimens was over eight times as great, and thus significantly higher ($P < 0.001$). The EZ after stabilization with USS (group C) was also significantly different ($P < 0.001$). The comparison between groups C and A showed identical results for NZ and ROM, but a significantly higher EZ ($P < 0.001$) after stabilization with USS.

Motion in group C after vertebral body replacement with Synex was significantly reduced compared to MOSS (for NZ $P = 0.024$; for EZ $P = 0.271$; for ROM $P = 0.029$). In the combination with Ventrofix (group A), no difference was apparent between the two replacement implants.

Table 3 Bisegmental motion (NZ, EZ, ROM) for lateral bending (mean value of left and right bending) in degrees, and *P*-values for the statistical comparison^a

	Intact specimen	Combined postero-anterior instrumentation Group C		Anterior instrumentation Group A	
		USS Synex	USS MOSS	Ventrofix Synex	Ventrofix MOSS
NZ (°)	1.55 ± 0.61	1.23 ± 0.58	1.33 ± 0.63	2.30 ± 1.96	2.50 ± 1.97
Comparison to intact specimen: P_{NZ}		0.270	0.435	0.196	0.129
Comparison of Synex and MOSS: P_{NZ}		0.212		0.319	
NZ (°)		1.28 ± 0.60		2.40 ± 1.92	
Comparison to intact specimen: P_{NZ}		0.211		0.056	
Comparison of groups C and A: P_{NZ}				0.011	
EZ (°)	3.70 ± 0.92	2.24 ± 0.50	2.42 ± 0.60	1.61 ± 0.74	1.71 ± 0.68
Comparison to intact specimen: P_{EZ}		<0.001	0.002	<0.001	<0.001
Comparison of Synex and MOSS: P_{EZ}		0.020		0.275	
EZ (°)		2.33 ± 0.55		1.66 ± 0.70	
Comparison to intact specimen: P_{EZ}		<0.001		<0.001	
Comparison of groups C and A: P_{EZ}				0.001	
ROM (°)	5.25 ± 1.23	3.47 ± 1.04	3.75 ± 1.20	3.92 ± 2.64	4.22 ± 2.58
Comparison to intact specimen: P_{ROM}		0.004	0.011	0.101	0.213
Comparison of Synex and MOSS: P_{ROM}		0.021		0.257	
ROM (°)		3.61 ± 1.11		4.07 ± 2.56	
Comparison to intact specimen: P_{ROM}		<0.001		0.069	
Comparison of groups C and A: P_{ROM}				0.429	

^a *t*-test, paired samples: individual comparison of the four different preparation states with the intact specimen (*first row*) and comparison between Synex and MOSS within groups C and A (*second*

row); *t*-test, independent samples: individual comparison between groups C and A and the intact specimen (*third row*) and comparison between groups C and A (*fourth row*)

Fig. 9 NZ, EZ, and ROM for rotation (mean value of motion to the left and right) of the intact specimen and the four implant combinations

With the intact specimens, and after stabilization with USS (group C), NZ, EZ and ROM for rotation toward the left and right were identical. After stabilization with Ventrofix (group A), the comparison between sides showed no differences for NZ or ROM, while the EZ was significantly lower (-0.3° ; $P = 0.008$) for rotation towards the left.

Discussion

The restoration of normal load-bearing in the anterior spine by means of a spacer implant has become a tried and tested procedure in tumour surgery and correction procedures involving the thoracic and lumbar spine [11, 26, 48, 49, 62, 64]. Injury-induced impairment of the axial load-bearing ability of the anterior spine is also considered by many authors to be an indication for reconstruction with a solid, load-bearing spacer, on the basis of clinical [10, 17, 18, 33, 34, 50] and biomechanical [1, 3, 20, 24, 41, 46, 53, 54, 61] investigations.

Synex is a new implant for vertebral body replacement for use in the thoracolumbar spine, and designed, on the one hand, to restore normal load-bearing in the anterior spine and, on the other, to avoid the disadvantage of additional morbidity resulting from strut graft harvesting from the iliac crest [2, 23, 59, 63, 72]. The titanium implant has already been investigated biomechanically in compression tests with human vertebral body specimens [37]: these showed significantly greater compressive force at the interface between implant and vertebral body, with reduced sinkage into the vertebral end-plate, for Synex compared to the “Harms mesh cage”.

Table 4 Bisegmental motion (NZ, EZ, ROM) for rotation (mean value of left and right rotation) in degrees, and *P*-values for the statistical comparison^a

	Intact specimen	Combined postero-anterior instrumentation Group C		Anterior instrumentation Group A	
		USS Synex	USS MOSS	Ventrofix Syne	Ventrofix MOSS
NZ (°)	0.44 ± 0.32	4.24 ± 2.07	5.56 ± 2.07	4.57 ± 1.79	5.32 ± 2.46
Comparison to intact specimen: P_{NZ}		< 0.001	< 0.001	< 0.001	< 0.001
Comparison of Synex and MOSS: P_{NZ}		0.024		0.141	
NZ (°)		4.90 ± 2.13		4.94 ± 2.14	
Comparison to intact specimen: P_{NZ}		< 0.001		< 0.001	
Comparison of groups C and A: P_{NZ}		0.941			
EZ (°)	1.69 ± 0.62	3.20 ± 0.33	3.35 ± 0.36	2.02 ± 0.46	2.24 ± 0.73
Comparison to intact specimen: P_{EZ}		< 0.001	< 0.001	0.088	0.043
Comparison of Synex and MOSS: P_{EZ}		0.271		0.190	
EZ (°)		3.27 ± 0.34		2.13 ± 0.61	
Comparison to intact specimen: P_{EZ}		< 0.001		0.052	
Comparison of groups C and A: P_{EZ}		< 0.001			
ROM (°)	2.13 ± 0.88	7.44 ± 2.27	8.90 ± 2.24	6.58 ± 2.17	7.56 ± 3.09
Comparison to intact specimen: P_{ROM}		< 0.001	< 0.001	< 0.001	< 0.001
Comparison of Synex and MOSS: P_{ROM}		0.029		0.108	
ROM (°)		8.17 ± 2.33		7.07 ± 2.66	
Comparison to intact specimen: P_{ROM}		< 0.001		< 0.001	
Comparison of groups C and A: P_{ROM}		0.134			

^a *t*-test, paired samples: individual comparison of the four different preparation states with the intact specimen (*first row*) and comparison between Synex and MOSS within groups C and A (*second*

row); *t*-test, independent samples: individual comparison between groups C and A and the intact specimen (*third row*) and comparison between groups C and A (*fourth row*)

The present biomechanical test series was designed to show the degree of bisegmental stability achievable with Synex in vitro, after complete corpectomy, when used in combination with USS in the postero-anterior procedure and with Ventrofix in the anterior approach. For comparison purposes, the “Harms mesh cage” was tested with the same implant combination, since, to the authors’ knowledge, this is currently the most commonly used titanium permanent implant used for vertebral body replacement in the thoracic and lumbar spine. According to a recent review of the literature, the posterior fixator system employed in this test series is likewise the most popular system [36]. An additional cross-linking element is regularly used in our procedure, on the basis of results from previous biomechanical test series [3]. No specific selection criteria were employed for the angularly stable anterior stabilization system, given the lack of our clinical experience in this respect.

The standards for test conditions and the handling of human specimens formulated by Wilke et al. [70] were taken into account and observed. We first determined the bone density of the specimens by DE-QCT [19, 28, 29, 30, 47, 57, 58, 60]. Reference ranges show considerable dispersion for trabecular bone density, with values of 86–145 mg/cm³ for the age range of 20–69 years [19]. Ito

et al. [29] measured values of 95.3–112.2 mg/cm³ for trabecular bone density and 228.8–379.0 mg/cm³ for cortical bone density. The bone density determined for our specimens was comparable to the in vivo values, although systematic error cannot be ruled out, since the measurements were performed on isolated specimens in a water bath.

Our test set-up met the conditions formulated by Panjabi et al. [52, 53, 54] for a flexible test system. It did not, however, permit the simulation of muscle forces, as presented by Wilke et al. [69]. Following the aforementioned recommendations, we applied loads with pure moments of 0–7.5 Nm [70] without any “external” axial preloading of the specimens. The bisegmental construction of T12–L2 was subjected to an unspecified axial preload through manual compression via USS or Ventrofix and the distraction of Synex. This corresponds to the intraoperative clinical procedure. All the operative steps in the tests were performed by one author (C.K.), thus ensuring as uniform an application as possible. For the purposes of standardization, and particularly for the determination of intervertebral, axially acting forces, the continuous measurement of pressure acting on the vertebral body replacement would have been desirable. Future investigations should consider the use of this force measurement to provide in-

Table 5 Test conditions of other biomechanical investigations [1, 3, 27, 31, 40, 49, 53, 54, 64] on the stability of human spinal specimens, including our own conditions and recommendations for standards [70]

Authors	Specimen (motion measurement)	Instrumentation	Load	Increase	Axial preload (compressive force)
Abumi et al. 1989 [1]	T11–L3, (T12–L1)	Intact; partial corpectomy; bisegmental stabilization: 3 posterior, 1 anterior implant; all in combination with strut graft	0–12 Nm	Increments of 4 Nm	150 N
Bastian et al. 1999 [3]	T10–L4, (T12–L2)	Intact; bisegmental stabilization: internal fixator with/without cross-linking; all without anterior stabilization	0–10 Nm	Continuous 0.3 Nm/s	?
Hitchon et al. 1999 [27]	T9–L3, (T12–L2)	Intact; corpectomy L1; bisegmental stabilization: 2 anterior plate systems; vertebral body replacement: wood block	0–6 Nm	Increments of 1.5 Nm	?
Kanayama et al. 1999 [31]	T11–L3, (T12–L2)	Intact; corpectomy L1; bisegmental stabilization: Kaneda SR; vertebral body replacement: iliac crest graft	0–3 Nm	Increments of 0.6 Nm	?
Oda et al. 1999 [49]	T11–L5, (L1–L3)	Intact; vertebrectomy L2; bisegmental stabilization: anterior Kaneda SR or combined Kaneda SR + ISOLA pedicle screw system; vertebral body replacement: Harms cage. Translations only determined.	0–4 Nm	Increments of 0.8 Nm	?
Panjabi et al. 1988 [53]	T9–L3, (T12–L1)	Intact; posterior instability (distraction injury), multisegmental stabilization: anterior Dunn, posterior Harrington or Luque system	0–15 Nm	Increments of 5 Nm	150 N
Panjabi et al. 1994 [54]	T11–L2, (T11–L1), (T12–L2)	Intact; burst fracture, not stabilized	0–7.5 Nm	Increments of 2.5 Nm	0 N
Vahldiek & Panjabi 1998 [64]	T12–L4, (L1–L3)	Intact; corpectomy L2, bisegmental stabilization: anterior, posterior or combined; vertebral body replacement: carbon-fibre cage CFK	0–7.5 Nm	Increments of 2.5 Nm	100 N
Kothe et al. 1997 [40]	T5–T10, T8–L1	Intact; burst fracture, bisegmental stabilization: posterior pedicle screw/plate system, no anterior stabilization	0–5 Nm	Gradual	?
Own test series	T10–L4, (T12–L2)	Intact; corpectomy L1; bisegmental stabilization: posterior or anterior; vertebral body replacement	0–7.5 Nm	Continuous 0.3 Nm/s	0 N
Recommendations by Wilke et al. 1998 [70]	Thoracic spine Lumbar spine	Intact; defined instability, defined instrumentation	0–5 Nm 0–7.5 Nm	0.5°/s–5.0°/s	?

formation about the forces transferred “directly” via a vertebral body replacement or transplant.

We determined the ranges of motion for the various movement directions using a precise electromagnetic measuring system with an error rate of approximately 2%. NZ, EZ and ROM were determined via three movement cycles according to the method described by Panjabi et al. and now recognized as the standard technique [52, 53, 70].

Other investigators working with human specimens have used differing test conditions to answer a variety of questions (Table 5). Because of certain differences in the test set-ups, the forces or moments used and the measuring systems for determining mono- or bisegmental ranges of motion, the results are only comparable to a limited extent (Table 6). Nevertheless, a comparison with the results described for the ROM of the intact specimen for the respective direction of movement can provide valuable information.

The average ROM of the intact spine in *flexion* was 5.6° in our own tests, compared to figures of 6°–6.2° described in the literature with comparable loads of 6–10 Nm [3, 27]. Kanayama et al. determined a value of 3.7° with a low load of 3 Nm [31]. Panjabi et al. measured a range of 7.9°–8.6° with a load of 7.5 Nm [54, 64]: one possible explanation for the higher ROM compared with our own tests is the differing test procedure, with gradual loading and a period of maximum loading exceeding 30 s. This difference in results, a difference that may also be due to the elasticity of the specimens employed, is likely to be systematic, since it was also observed for the other movement directions.

A range of 2.7°–4.0° was observed for the monosegmental ROM with higher loads of 12–15 Nm [1, 53]. This roughly corresponds to half the bisegmental ROM measured by ourselves.

The stability obtained with differing methods of anterior instrumentation was lower than with posterior tech-

Table 6 Results of other biomechanical investigations [1, 3, 27, 31, 40, 49, 53, 54, 64] on the stability of human spinal specimens, including our own results for comparison purposes; (values in *italics* taken from graphs)

Authors	Motion measurement	Max. load	Instrumentation	Flexion (ROM)	Extension (ROM)	Lateral bending (ROM)	Rotation (ROM)
Abumi et al. 1989 [1]	Monosegmental: T12–L1	12 Nm	Intact	4.0°	2.7°	3.5°	1.3°
			Kaneda, cross-linking	2.6°	1.9°	1.1°	2.9°
			External fixator	0.8°	0.6°	1.4°	1.3°
			Harrington compression system	1.0°	1.0°	3.0°	2.0°
Bastian et al. 1999 [3]	Bisegmental: T12–L2	10 Nm	Intact	6.2°	5.0°	7.2°	1.5°
			Internal fixator without cross-linking	2.9°	3.2°	2.3°	5.7°
			Internal fixator with cross-linking	2.6°	3.2°	2.2°	4.4°
Hitchon et al. 1999 [27]	Bisegmental: T12–L2	6 Nm	Intact	6°	6°	6°	2°
			Kaneda SR ^a	6°	4.4°	2°/2.5°	3°/2.5°
			ATLP ^a	3.5°	9.3°	3.5°/4°	5°/3°
Kanayama et al. 1999 [31]	Bisegmental: T12–L2	3 Nm	Intact	3.7°	3.9°	6.7°	2.4°
			Kaneda SR with strut graft ^a	2.1°	2.7°	2.6°/3.2°	2.0°/2.1°
			(values calculated from stiffness)				
Oda et al. 1999 [49]	Bisegmental: L1–L3	4 Nm	Intact	2.5 mm	2.5 mm	5.5 mm	Ø
			Kaneda SR + ISOLA pedicle screw system	1.1 mm	1.1 mm	0.7 mm	Ø
			Kaneda SR	2.1 mm	2.1 mm	1.7 mm	Ø
Panjabi et al. 1988 [53]	Monosegmental: T12–L1	15 Nm	Intact	2.7°	2.0°	3.4°	2.0°
			Dunn system anterior	7.6°	4.2°	2.7°	8.5°
			Harrington compression system	2.2°	1.2°	5.2°	8.5°
			Luque short right-angled	3.3°	3.5°	6.4°	6.6°
Panjabi et al. 1994 [54]	Bisegmental: T11–L1; T12–L2	7.5 Nm	Intact	7.9°	6.8°	8.0°	2.9°
			Burst fracture of T12 or L1 (without stabilization)	17.6°	12.4°	21.3°	11.7°
Vahldiek & Panjabi 1998 [64]	Bisegmental: L1–L3	7.5 Nm	Intact	8.6°	8.2°	7.3°	2.7°
			BWM anterior	5.7°	6.9°	5.6°	5.1°
			Internal fixator posterior (BWM or DFS)	0.8°	1.3°	2.9°	2.8°
			Combined BWM (1 rod) + internal fixator	0.8°	1.3°	2.1°	2.0°
			Combined BWM (2 rods) + internal fixator	0.8°	0.9°	1.6°	1.6°
Kothe et al. 1997 [40]	Thoracic spine; bisegmental (?)	5 Nm	Intact	6.2°	6.2°	10.6°	12.1°
			Vertebral body fracture, internal fixator, cross-linking	1.5°	1.5°	10.0°	3.6°
Own test series	Bisegmental: T12–L2	7.5 Nm	Intact	5.6°	4.4°	5.3°	2.1°
			USS (cross-linking) + Synex	1.1°	3.4°	3.5°	7.4°
			USS (cross-linking) + MOSS	1.3°	6.0°	3.8°	8.9°
			Ventrofix + Synex	6.6°	4.2°	3.9°	6.6°
			Ventrofix + MOSS	6.8°	5.3°	4.2°	7.6°

^aSeparate figures for lateral bending and rotation: R/L

niques; some authors reported a reduced ROM [1, 27, 31, 49, 64], while others observed identical or reduced stability compared to the intact spine [27, 53]. In our own tests, we observed a greater degree of motion with Ventrofix. The differing conclusions reported in the literature reflect

the biomechanical differences in the systems and methods of vertebral body replacement under investigation. In the highly unstable situation after complete corpectomy prevailing in our own tests, stability could not even be achieved for the intact specimen after anterior stabiliza-

tion with Ventrofix – irrespective of the type of vertebral body replacement. We therefore consider this procedure to be inadequate in this situation.

A high degree of stability, with a ROM of less than 1.5° , was achieved with USS. Confirming our own results, all authors also observed clearly reduced motion after posterior stabilization [1, 3, 49, 53, 64].

The average ROM of the intact specimen observed for *extension* in our own test series was 4.4° . The literature reports a range of 5.0° – 8.2° with loads of 6–10 Nm [3, 27, 53, 54] and a figure of 3.9° with 3 Nm [31]. In comparison with the intact spine, the instability could not be adequately reduced using the anterior technique [1, 27, 31, 49, 64]. In some cases, even greater motion was reported after anterior instrumentation [27, 53].

With similar ROMs after posterior and anterior stabilization in our own test series, a significantly higher NZ after anterior stabilization indicated reduced stability. The type of vertebral body replacement also had a considerable influence on the degree of rigidity achieved: at least comparable stability could be achieved with Synex, in combination with both Ventrofix and USS. With the “Harms mesh cage” the construction proved less stable than the intact specimen.

The ROMs reported in the literature for *lateral bending* of the intact spine [3, 27, 31, 54, 64], ranging from 6° to 8° , were higher than the mean value of 5.3° observed by us. Stability was achieved with all implant combinations and stabilization techniques [1, 3, 27, 31, 49, 64], apart from the extended posterior systems tested by Panjabi et al. [53], where the measured ROM was doubled using Harrington and Luque rods.

In our own tests, we also managed to achieve a lower ROM with all implant combinations, compared to the intact spine. This difference was statistically significant after stabilization with USS, while a trend in favour of greater stability was observed for the anterior technique with Ventrofix. The comparison of the vertebral body replacement implants showed a small, but statistically significant, difference in favour of Synex in combination with USS. For the sake of convenience, we have reported the mean of the measurements for left- and right-sided motion for lateral bending and rotation, as is usual in the literature. As expected, we did not observe any differences in the movement deflections toward the right and left for the intact spine or for symmetrical posterior stabilization with USS. After stabilization with Ventrofix, by contrast, the EZ and ROM measurements differed significantly: the reduced motion for the lateral bending to the right was attributable to the fact that the implant mounted on the left was under tension, with the vertebral body replacement acting as the opposing compression-resistant element. With the lateral bending to the left, on the other hand, the lesion “swings open”, with no limiting restriction, against the elastic resistance of Ventrofix.

The smallest movement deflections of the intact thoracolumbar spine are reported for *rotation* [1, 3, 27, 31, 54, 64]. The average ROM of 2.1° observed in our tests corresponds to the figures cited by others of between 1.5° and 2.7° [3, 27, 31, 54, 64]. By contrast, in thoracic sections of the spine, where rotational ROM is highest in comparison with the other directions of motion, ROM is cited as 12.1° (5 Nm) [40], which illustrates the anatomically differing mode of construction.

Our own results illustrate that adequate axial stability of the thoracolumbar spine after complete corpectomy cannot be achieved with an implant: in our test series the rotational stability of all implant combinations was significantly lower than that of the intact specimen ($P < 0.001$ for NZ and ROM in the four groups). Many authors have likewise been unable to achieve the stability of the intact spine with any material combination [1, 3, 27, 53]. Vahldiek and Panjabi [64] also performed a corpectomy: after stabilization with an implant, whether anteriorly or posteriorly, the ROM was still greater than the intact range. Only by combining two stabilizing implants posteriorly and anteriorly were they able to reduce the motion to below that of the intact specimen. In contrast to others [1, 27], the group of authors working with Kaneda himself [31] and Zdeblick et al. [74] achieved a higher rigidity than that of the intact spine, including for rotation, using the Kaneda SR as an anteriorly stabilizing implant.

In our test series, the NZ and ROM values for the four implant combinations were 9–12 times and 3–4 times higher than those determined for the intact specimen. This may equate to an inadequately stable situation in vivo. No significant differences were apparent in the comparison between posterior and anterior stabilization, while the comparison between Synex and MOSS showed reduced motion for Synex in each case, regardless of the type of stabilization employed. For the combination with USS, the difference was significant ($P < 0.03$ for NZ, ROM).

Several authors have compared anterior and posterior stabilization techniques: Abumi et al. [1] described as “adequate” the stability achieved with an external fixator in a model with posterior instability in the form of a distraction injury. Like other authors [3, 20], they mentioned that three-dimensional stability can be enhanced with the cross-linking provided in a two-rod system. Kanayama et al. [31] assessed the rigidity of an anterior system as appropriate and adequate for a corpectomy or subtotal vertebrectomy of the thoracolumbar spine. Only for a total vertebrectomy did they recommend combined posterior and anterior stabilization. Shono et al. [61] stated that anterior stabilization alone is biomechanically superior to posterior transpedicular fixation, providing higher rigidity. Zdeblick et al. [74] likewise assessed a purely anterior approach as suitable and effective in restoring spinal stability. By contrast, Vahldiek and Panjabi [64] considered a solely anterior procedure as inadequate even after complete corpectomy, and recommended a posterior, or better

still a combined postero-anterior, stabilizing technique. Oda et al. [49] observed increased rigidity, compared to the intact situation, for all movement directions only with combined postero-anterior stabilization. This degree of stability could not be achieved with either posterior or anterior instrumentation alone.

In our own flexion tests, we managed to achieve a definite gain in stability only with posterior instrumentation, in contrast to the purely anterior approach. We cannot, on the basis of our own results, predict whether the rigidity resulting from stabilization with Ventrofix can also achieve the goal of bony fusion, although the five-fold higher ROM suggests that the stability may not prove adequate in this respect. For most movement directions, additional stabilization can be expected to be provided in vivo by the anterior longitudinal ligament, which is generally not affected in injuries, and thus needs to be preserved [8]. The ligament can contribute to a distinct reduction in ROM during rotation, though hardly providing any stabilization during flexion, when the load tends to be taken off the ligament.

Several authors refer to the importance of intervertebral, implant-mediated compression of the vertebral body replacement or transplant [1, 49]. The stabilizing effect of such intervertebral compression or "tensioning" is supported by the results of our tests: the intervertebral distraction of Synex after insertion into the defect was shown to induce this type of "tensioning" in the system. We observed reduced motion with this vertebral body replacement for all directions in combination with USS. The difference between the Synex/USS and the MOSS/USS combinations was greatest for extension. We attributed this to the fact that a significant proportion of the internal fixator's elastic "spring travel" is avoided using Synex, thanks to the anterior bracing, and motion was reduced accordingly. To sum up: we viewed the intervertebral "tensioning" as a reason for the increased stability of the construction with Synex.

In using the "Harms cage", we were likewise attempting to achieve intervertebral compression via the vertebral body implant holder through the posterior "post-tensioning" of the fixator. The results showed that a comparable effect was almost impossible to achieve, even with meticulous implementation of the technique. In fact, a "third surgical step" was required after the insertion of MOSS to achieve this end, which would have entailed significantly increased expenditure, an additional burden and increased surgical risk for the patient.

Conclusions

Synex is a new, titanium vertebral body replacement implant whose biomechanical properties suggest that it should be at least as suitable as the hitherto widely used "Harms mesh cage". Comparing Synex with MOSS in combination with USS, a significantly higher stability was noted with Synex for extension, lateral bending, and axial rotation. We would therefore expect Synex to provide increased stability in vivo, with less postoperative loss of correction and a reduced risk of implant dislocation or kyphosis.

Significantly higher stability was achieved with USS in comparison with Ventrofix for flexion, extension, and lateral bending. We therefore consider a combined approach to be superior in vivo.

For rotation, a degree of stability matching that of the intact specimen could not be achieved with any implant combination. In a comparable situation in vivo with complete corpectomy, *including removal of the anterior longitudinal ligament*, a combined posterior and anterior stabilization should therefore be considered in combination with the vertebral body replacement.

Acknowledgements We would like to thank Stratec Medical, Oberdorf, Switzerland, for providing funding for this project.

References

1. Abumi K, Panjabi MM, Duranceau J (1989) Biomechanical evaluation of spinal fixation devices. III. Stability provided by six spinal fixation devices and interbody bone graft. *Spine* 14: 1249–1255
2. Banwart JC, Asher MA, Hassanein RS (1995) Iliac crest bone graft harvest donor site morbidity. A statistical evaluation. *Spine* 20:1055–1060
3. Bastian L, Knop C, Lange U, Blauth M (1999) Einfluß eines Querverbinders oder einer Cerclage auf die mechanische Stabilität des Fixateur interne. *Orthopäde* 28:714–722
4. Bayley JC, Yuan HA, Fredrickson BE (1991) The Syracuse I-plate. *Spine* 16 [3 Suppl]:120–124
5. Been HD (1991) Anterior decompression and stabilization of thoracolumbar burst fractures by the use of the Slot-Zielke device. *Spine* 16:70–77
6. Beisse R, Potulski M, Bühren V (1999) Thorakoskopisch gesteuerte ventrale Plattenspondylodese bei Frakturen der Brust- und Lendenwirbelsäule. *Operat Orthop Traumatol* 11:54–69
7. Blauth M, Knop C, Bastian L, Lobenhoffer P (1997) Neue Entwicklungen in der Chirurgie der verletzten Wirbelsäule. *Orthopäde* 26:437–449
8. Blauth M, Knop C, Bastian L (1998) Brust- und Lendenwirbelsäule. In: Tscherne H, Blauth M (eds) *Tscherne Unfallchirurgie – Wirbelsäule*, 1st edn. Springer, Berlin Heidelberg New York, pp 241–372
9. Blauth M, Knop C, Bastian L, Krettek C, Lange U (1998) Komplexe Verletzungen der Wirbelsäule. *Orthopäde* 27: 17–31
10. Bohlman HH (1985) Treatment of fractures and dislocations of the thoracic and lumbar spine. *J Bone Joint Surg Am* 67:165–169

11. Böhm H, Harms J, Donk R, Zielke K (1990) Correction and stabilization of angular kyphosis. *Clin Orthop* 258:56–61
12. Bühren V, Beisse R, Potulski M (1997) Minimal-invasive ventrale Spondylodesen bei Verletzungen der Brust- und Lendenwirbelsäule. *Chirurgie* 68: 1076–1084
13. Daniaux H (1986) Transpedikuläre Reposition und Spongiosaplastik bei Wirbelkörperbrüchen der unteren Brust- und Lendenwirbelsäule. *Unfallchirurg* 89:197–213
14. Daniaux H, Seykora P, Genelin A, Lang T, Kathrein A (1991) Application of posterior plating and modifications in thoracolumbar spine injuries. Indication, techniques and results. *Spine* 16 [3 Suppl]:125–133
15. Dick W (1987) The “fixateur interne” as a versatile implant for spine surgery. *Spine* 12:882–900
16. Esses SI, Botsford DJ, Kostuik JP (1990) Evaluation of surgical treatment for burst fractures. *Spine* 15:667–673
17. Feil J, Wörsdörfer O (1992) Komplikationen bei der operativen Versorgung von Wirbelsäulenverletzungen. *Langenbecks Arch Chir Suppl Kongressbd*: 304–310
18. Feil J, Wörsdörfer O (1992) Ventrale Stabilisierung im Bereich der Brust- und Lendenwirbelsäule. *Chirurg* 63: 856–865
19. Felsenberg D, Kalender WA, Banzer D, Schmilinsky G, et al (1988) Quantitative computertomographische Knochenmineralgehaltsbestimmung. *Fortschr Röntgenstr* 148:431–436
20. Gaines RW Jr, Carson WL, Satterlee CC, Groh GI (1991) Experimental evaluation of seven different spinal fracture internal fixation devices using nonfailure stability testing. The load-sharing and unstable-mechanism concepts. *Spine* 6:902–909
21. Gertzbein SD, Court Brown CM, Jacobs RR, Marks P, et al (1988) Decompression and circumferential stabilization of unstable spinal fractures. *Spine* 13:892–895
22. Gotzen L, Junge A, Koppelberg T, Stiletto R (1995) Fortschritte in der Fixateur-interne-Stabilisierung von thorakolumbalen Wirbelsäulenverletzungen. *Unfallchirurg* 98:79–86
23. Goulet JA, Senunas LE, De Silva GL, Greenfield ML (1997) Autogenous iliac crest bone graft. Complications and functional assessment. *Clin Orthop* 339:76–81
24. Gurwitz GS, Dawson JM, McNamara MJ, Federspiel CF, Spengler DM (1993) Biomechanical analysis of three surgical approaches for lumbar burst fractures using short-segment instrumentation. *Spine* 18:977–982
25. Haas N, Blauth M, Tscherne H (1991) Anterior plating in thoracolumbar spine injuries. Indication, technique, and results. *Spine* 16 [Suppl 3]:100–111
26. Heller JG, Zdeblick TA, Kunz DA, McCabe R, Cooke ME (1993) Spinal instrumentation for metastatic disease: in vitro biomechanical analysis. *J Spinal Disord* 6:17–22
27. Hitchon PW, Goel VK, Rogge T, Grosland NM, Torner J (1999) Biomechanical studies on two anterior thoracolumbar implants in cadaveric spines. *Spine* 24:213–218
28. Ho CP, Kim RW, Schaffler MB, Sartoris DJ (1990) Accuracy of dual-energy radiographic absorptiometry of the lumbar spine: cadaver study. *Radiology* 176:171–173
29. Ito M, Hayashi K, Yamada M, Uetani M, Nakamura T (1993) Relationship of osteophytes to bone mineral density and spinal fracture in men. *Radiology* 189:497–502
30. Kalender WA (1988) Neue Entwicklungen in der Knochendichtemessung mit quantitativer Computertomographie (QCT). *Radiologe* 28:173–178
31. Kanayama M, Ng JTW, Cunningham BW, Abumi K, Kaneda K, McAfee PC (1999) Biomechanical analysis of anterior versus circumferential spinal reconstruction for various anatomic stages of tumor lesions. *Spine* 24:445–450
32. Kaneda K, Taneichi H, Abumi K, Hashimoto T, Satoh S, Fujiya M (1997) Anterior decompression and stabilization with the Kaneda device for thoracolumbar burst fractures associated with neurological deficits. *J Bone Joint Surg Am* 79:69–83
33. Knop C, Blauth M, Bastian L, Lange U, Kesting J, Tscherne H (1997) Frakturen der thorakolumbalen Wirbelsäule – Spätergebnisse nach dorsaler Instrumentierung und ihre Konsequenzen. *Unfallchirurg* 100:630–639
34. Knop C, Bastian L, Lange U, Blauth M (1999) Transpedikuläre Spongiosaplastik am thorakolumbalen Übergang – klinische, röntgenologische und computertomographische Ergebnisse. *Orthopäde* 28:703–713
35. Knop C, Blauth M, Bühren V, Hax P-M, et al (1999) Operative Behandlung von Verletzungen des thorakolumbalen Übergangs. 1. Epidemiologie. *Unfallchirurg* 102:924–935
36. Knop C, Blauth M, Bühren V, Hax P-M, et al (2000) Operative Behandlung von Verletzungen des thorakolumbalen Übergangs. 2. Operation und röntgenologische Befunde. *Unfallchirurg* (in press)
37. Knop C, Lange U, Bastian L, Blauth M (2000) Biomechanical compression tests with a new implant for thoracolumbar vertebral body replacement. *Eur Spine J* (submitted)
38. Kossman T, Ertel W, Platz A, Trentz O (1999) Die kombinierte Operation von Frakturen des thorakolumbalen Übergangs mit der Inlay-Span-Technik. *Orthopäde* 28:432–440
39. Kostuik JP (1988) Anterior fixation for burst fractures of the thoracic and lumbar spine with or without neurological involvement. *Spine* 13:286–293
40. Kothe R, Panjabi MM, Liu W (1997) Multidirectional instability of the thoracic spine due to iatrogenic pedicle injuries during transpedicular fixation. A biomechanical investigation. *Spine* 22:1836–1842
41. Krag MH (1991) Biomechanics of thoracolumbar spinal fixation. A review. *Spine* 16 [3 Suppl]:84–99
42. Kurz LT, Garfin SR, Booth RE Jr (1989) Harvesting autogenous iliac bone grafts. A review of complications and techniques. *Spine* 14:1324–1331
43. Liljenqvist U, Mommensen U (1995) Die operative Behandlung thorakolumbalen Wirbelsäulenverletzungen mit dem Fixateur interne und transpedikulärer Spongiosaplastik. *Unfallchirurgie* 21: 30–39
44. Lindsey RW, Dick W (1991) The fixateur interne in the reduction and stabilization of thoracolumbar spine fractures in patients with neurologic deficit. *Spine* 16 [3 Suppl]:140–145
45. Magerl F, Aebi M, Gertzbein SD, Harms J, Nazarian S (1994) A comprehensive classification of thoracic and lumbar injuries. *Eur Spine J* 3:184–201
46. Maiman DJ, Pintar F, Yoganandan N, Reinartz J (1993) Effects of anterior vertebral grafting on the traumatized lumbar spine after pedicle screw-plate fixation. *Spine* 18:2423–2430
47. McBroom RJ, Hayes WC, Edwards WT, Goldberg RP, White AA III (1985) Prediction of vertebral body compressive fracture using quantitative computed tomography. *J Bone Joint Surg Am* 67:1206–1214
48. Mutschler W, Wirbel R (1997) Pathologische Frakturen. *Unfallchirurg* 100: 410–429
49. Oda I, Cunningham BW, Abumi K, Kaneda K, McAfee PC (1999) The stability of reconstruction methods after thoracolumbar total spondylectomy. *Spine* 24:1634–1638
50. Okuyama K, Abe E, Chiba M, Ishikawa N, Sato K (1996) Outcome of anterior decompression and stabilization for thoracolumbar unstable burst fractures in the absence of neurologic deficits. *Spine* 21:620–625

51. Olerud S, Karlstrom G, Sjoström L (1988) Transpedicular fixation of thoracolumbar vertebral fractures. *Clin Orthop* 227:44–51
52. Panjabi MM (1988) Biomechanical evaluation of spinal fixation devices. I. A conceptual framework. *Spine* 13:1129–1134
53. Panjabi MM, Abumi K, Duranceau J, Crisco JJ (1988) Biomechanical evaluation of spinal fixation devices. II. Stability provided by eight internal fixation devices. *Spine* 13:1135–1140
54. Panjabi MM, Oxland TR, Lin RM, McGowen TW (1994) Thoracolumbar burst fracture. A biomechanical investigation of its multidirectional flexibility. *Spine* 19:578–585
55. Pickel H, Hofmeister M, Mückley T, Bühren V (1997) Schicksal der transpedikulären Spongiosaplastik nach Frakturversorgung. *Hefte Zeitschr Unfallchirurg* 268:251
56. Potulski M, Beisse R, Bühren V (1999) Die thorakoskopisch gesteuerte Behandlung der "vorderen Säule" – Technik und Ergebnisse. *Orthopäde* 28:723–730
57. Reinbold WD, Adler CP, Kalender WA, Lente R (1991) Accuracy of vertebral mineral determination by dual-energy quantitative computed tomography. *Skeletal Radiol* 20:25–29
58. Resch A, Schneider B, Bernecker P, Battmann A, et al (1995) Risk of vertebral fractures in men: relationship to mineral density of the vertebral body. *AJR* 164:1447–1450
59. Sawin PD, Traynelis VC, Menezes AH (1998) A comparative analysis of fusion rates and donor-site morbidity for autogeneic rib and iliac crest bone grafts in posterior cervical fusions. *J Neurosurg* 88:255–265
60. Seeger LL (1997) Bone density determination. *Spine* 22 [Suppl]:49–57
61. Shono Y, McAfee PC, Cunningham BW (1994) Experimental study of thoracolumbar burst fractures. A radiographic and biomechanical analysis of anterior and posterior instrumentation systems. *Spine* 19:1711–1722
62. Stoltze D, Harms J (1999) Korrekturen posttraumatischer Fehlstellungen – Prinzipien und Techniken. *Orthopäde* 28:731–745
63. Summers BN, Eisenstein SM (1989) Donor site pain from the ilium. A complication of lumbar spine fusion. *J Bone Joint Surg Br* 71:677–680
64. Vahldiek MJ, Panjabi MM (1998) Stability potential of spinal instrumentations in tumor vertebral body replacement surgery. *Spine* 23:543–550
65. von Gumpfenberg S, Vieweg J, Claudi B, Harms J (1991) Die primäre Versorgung der frischen Verletzungen von Brust- und Lendenwirbelsäule. *Aktuelle Traumatol* 21:265–273
66. Wawro W, Konrad L, Aebi M (1994) Die monosegmentale Montage des Fixateur interne bei der Behandlung von thorakolumbalen Wirbelfrakturen. *Unfallchirurg* 97:114–120
67. Weckbach A, Vogel S (1997) Einfluß der transpedikulären intercorporellen Spongiosaplastik auf den Korrekturverlust nach alleiniger dorsaler Instrumentierung thoracolumbaler Wirbelsäulenverletzungen. *Hefte Zeitschr Unfallchirurg* 268:205–208
68. White AA, III, Panjabi MM (1990) *Clinical biomechanics of the spine*, 2nd edn. Lippincott, Philadelphia
69. Wilke HJ, Claes L, Schmitt H, Wolf S (1994) A universal spine tester for in vitro experiments with muscle force simulation. *Eur Spine J* 3:91–97
70. Wilke HJ, Wenger K, Claes L (1998) Testing criteria for spinal implants: recommendations for the standardization of in vitro stability testing of spinal implants. *Eur Spine J* 7:148–154
71. Wippermann BW, Schratt HE, Steeg S, Tschern H (1997) Komplikationen der Spongiosaentnahme am Beckenkamm. Eine retrospektive Analyse von 1191 Fällen. *Chirurg* 68:1286–1291
72. Younger EM, Chapman MW (1989) Morbidity at bone graft donor sites. *J Orthop Trauma* 3:192–195
73. Yuan HA, Mann KA, Found EM, Helbig TE, et al (1988) Early clinical experience with the Syracuse I-Plate: an anterior spinal fixation device. *Spine* 13:278–285
74. Zdeblick TA, Warden KE, Zou D, McAfee PC, Abitbol JJ (1993) Anterior spinal fixators. a biomechanical in vitro study. *Spine* 18:513–517