Combined anteroposterior spinal fixation provides superior stabilisation to a single anterior or posterior procedure

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Fusion is the main goal in the surgical management of the injured and unstable spine. A wide variety of implants is available to enhance this. Our study was performed to evaluate the stabilising characteristics of several anterior, posterior and combined systems of fixation. Six thoracolumbar (T11 to L2) spines from 13-week-old calves were first tested intact. Then the vertebral body of T13 was removed and the defect replaced and supported by a wooden block to simulate bone grafting. Dorsal implants consisting of a Universal Spine System (USS) fracture system and an AO *Fixateur interne* (AOFI), and ventral implants comprising of a Kaneda Classic, a Kaneda SR, a prototype of the VestroFix single clamp/single rod construct (SC/SR) and the VestroFix single clamp/double rod construct (SC/DR) were first implanted individually to stabilise the removal of the vertebral body. Simulating the combined anteroposterior stabilisations, all ventral implants were combined with the AOFI. The range of motion (ROM) was measured under loads of up to 7.5 Nm. The load was applied in a custom-made spine tester in the three primary directions while measuring the intervertebral movements using a goniometric linkage system.

The dorsal systems limited ROM in flexion below 0.9° and in extension between 3.3° and 3.6° (median values). The improved Kaneda System SR yielded a mean ROM of 1.8° in flexion and in extension. The median rotation found with the VestroFix (SC/DR) was 3.2° for flexion and 2.8° for extension.

Reinforcement of the ventral constructs with a dorsal system reduced the ROM in flexion and extension in all cases to 0.4° and lower.

In rotation, the median ROM of the anterior systems ranged from 2.7° to 5.1° and for the posterior systems from 3.9° to 5.7°, while the combinations provided a ROM of 1.2° to 1.9°. In lateral bending, the posterior implants restricted movement to 1.1°, whereas the anterior implants allowed up to 5.2°. The combined systems provided the highest stability at less than 0.6°.

Our study revealed distinct differences between posterior and anterior approaches in all primary directions. Also, different stabilisation characteristics were found within the anterior and posterior groups. Combinations of these two approaches provided the highest stability in all directions.

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A variety of implants is available for the surgical management of the severely injured spine. The decision to stabilise the spine anteriorly or posteriorly depends on many factors, including the mechanism and type of injury, the presence of neurological deficit and the overall medical condition of the patient.

The indications for both anterior¹⁻⁴ and posterior^{1,5-8} stabilisation include fractures, tumours and deformities of the spine. A combination of anterior and posterior fixation is indicated in severe destruction of vertebral bodies or gross fracture-dislocation.^{1,9,10}

The advantages of posterior pedicle fixation systems like the AO *Fixateur interne* (AOFI)⁴ include the long lever arms of the Schanz pedicle screws,^{5,11} the ligamentotaxis of retropulsed bone fragments,^{9,11} firm anchorage¹² and safe and easy access.^{5,9} In long-term follow-up, however, some loss of kyphotic reduction has been observed with such systems.^{5,7,13}

The advantages of anterior fixation with implants like the Kaneda system¹⁴ are better decompression of the spinal canal and reconstruction of the anterior load-bearing column,^{1,15,16} combined with excellent visibility.¹⁵ With an anterior approach, however, the surgeon comes in close

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contact with vital structures. Also, blood loss and morbidity are higher than with a posterior approach.⁹

Numerous studies have been performed on the biomechanical performance of single anterior or posterior fixation. Although severe instability of the spine requires combined anteroposterior fixation,^{1,9,10} there are few biomechanical data on this procedure.

Knowledge of the biomechanical performance of various methods of spinal fixation is the basis for choosing the method of stabilisation. Our aim was to evaluate the hypothesis of the superiority of combined anteroposterior spinal fixation over single anterior or posterior fixation

Materials and Methods

We used six fresh-frozen thoracolumbar (T11 to L2) spines from calves of the Rotfleck breed aged 13 weeks and weighing 180 to 200 kg. Before testing, all muscles and soft tissue were removed. Care was taken not to damage the ligamentous and bony structures. The T11 and the L2 vertebrae were embedded in polymethylmethacrylate (Technovit 3040; Heraeus Kulzer, Wehrheim Ts, Germany) and connectors were fixed to this material in order to attach the specimens to a custom-made spine tester.¹⁷

We performed non-destructive three-dimensional flexibility tests on the spines in flexion/extension ($\pm M_x$), left/right axial rotation ($\pm M_y$) and right/left lateral bending ($\pm M_z$). Pure moments were applied in continuous cycles and in alternating sequences at a constant rate of 1.1°/s. Loads of up to 7.5 Nm were applied by stepper motors integrated into the spine tester (Fig. 1). During testing the spines were allowed to move unconstrained in all remaining five degrees of freedom. To minimise the viscoelastic effect, data were collected on the third cycle. Three-dimensional movement at the segments T12 to L1 was measured by a goniometric linkage system¹⁸ (Fig. 1). The specimens were exposed to air during testing but were kept moist in wrapping of gauze soaked in saline.

Each specimen underwent the following protocol in the same order (Fig. 2): 1) intact testing; 2) resection of the vertebral body of T13 and the adjacent discs, and bridging of the defect by a wooden block to simulate bone grafting; 3) stabilisation by a) the posterior AOFI (Synthes), b) the posterior Universal Spine System (USS) for fractures (Synthes) (the two systems using the same Schanz pedicle screws), c) the Kaneda Classic (Kaneda CI) (AcroMed) as an anterolateral implant, d) the Kaneda Smooth Rod (Kaneda SR) (AcroMed), e) the Ventrifix (Synthes) single clamp/single rod construct (SC/SR) with two Ventrifix single clamps on each side of the lesion, which is only recommended for the mid and upper thoracic spine, and f) a prototype, not commonly used, of the Ventrifix (Synthes) single clamp/double rod construct (SC/DR) with two single clamps on each side of the corpectomy and reinforced by the Ventrifix double-rod clamp. Since we had to use the same screw holes for all anterior systems, they had

Fig. 1

Intact specimen fixed in the spine tester with a three-dimensional goniometric linkage system attached.

to be tested in a defined order according to increasing screw diameter. Finally, each anterior implant was tested in combination with the posterior AOFI.

The range of motion (ROM), the neutral zone (NZ), two parameters of stiffness and the area enclosed by the load-deformation curve were determined.¹⁹ Due to the considerable amount of stabilisation utilised in the study, only the ROM, which is generally considered the salient parameter in such testing, is reported. It was defined as the angular deformation at maximum load. As the anterior fixation systems were attached to the specimens in an asymmetrical position, we differentiated between left and right axial rotation and right and left lateral bending.

Statistical analysis was performed using the Wilcoxon signed-rank test for each paired group. Differences in the ROM were considered to be significant at $p < 0.05$. The level of significance was not adjusted to allow for the large number of comparisons. None of the results would have been significant after the adjustment. Instead, we preferred not to alter the p value to indicate the superior strength of combined anteroposterior fixation.

Results

The posterior fixation systems with the interbody graft reduced the ROM in flexion to 0.4° to 0.9° (median values) and lateral bending to 1.1° (Tables I and II), and there was

Fig. 2

Intact, injured, and instrumented specimens in the spine tester.

Table I. Biomechanical properties of calf spines (T12 to L1) with posterior, anterior and combined spinal fixation systems for flexion/extension (degrees)

Moment + 7.5 Nm	Extension		Flexion	
	Median	Range	Median	Range
Intact	2.8	2.3 to 3.0	5.5	4.8 to 7.2
USS fracture system	3.6	3.0 to 4.6	0.9	0.4 to 1.9
AOFI	3.3	2.1 to 4.1	0.4	0.2 to 1.5
Kaneda Classic	1.8	1.3 to 2.5	2.0	1.4 to 2.3
Kaneda SR	2.0	1.1 to 2.5	1.8	1.1 to 2.4
VentroFix SC/SR	3.2	2.5 to 3.4	4.5	3.2 to 6.1
VentroFix SC/DR	2.8	1.2 to 3.9	3.2	2.3 to 6.7
Kaneda Classic + AOFI	0.3	0.2 to 0.5	0.3	0.1 to 0.5
Kaneda SR + AOFI	0.3	0.2 to 0.4	0.2	0.1 to 0.3
Ventrofix SC/SR+ AOFI	0.4	0.2 to 0.6	0.3	0.3 to 0.4
VentroFix SC/DR+ AOFI	0.3	0.2 to 0.5	0.3	0.1 to 0.4

Table II. Biomechanical properties of calf spines (T12 to L1) with posterior, anterior and combined spinal fixation systems for right/left lateral bending (degrees)

Moment+7.5 Nm	Lateral bending left		Lateral bending right	
	Median	Range	Median	Range
Intact	9.6	7.3 to 10.1	9.2	7.4 to 10.0
USS fracture system	1.1	0.8 to 1.5	1.1	1.0 to 1.8
AOFI	1.1	0.5 to 1.8	0.9	0.7 to 2.0
Kaneda Classic	4.4	1.5 to 5.9	3.2	1.5 to 4.0
Kaneda SR	3.0	1.7 to 3.9	2.9	0.3 to 4.4
VentroFix SC/SR	5.2	2.9 to 5.9	2.7	1.2 to 6.7
VentroFix SC/DR	4.7	1.9 to 5.7	3.5	1.0 to 7.1
Kaneda Classic + AOFI	0.6	0.3 to 0.9	0.6	0.3 to 0.8
Kaneda SR + AOFI	0.6	0.3 to 0.8	0.6	0.0 to 0.6
Ventrofix SC/SR+ AOFI	0.8	0.4 to 0.9	0.7	0.5 to 0.9
VentroFix SC/DR+ AOFI	0.7	0.4 to 0.9	0.8	0.4 to 1.0

no great difference between the AOFI and the posterior USS fracture system (Tables III and IV). With 3.3° to 3.6° in extension and 3.9° to 5.7° in axial rotation, the ROM with the posterior implants was greater than that of the intact spine with 2.8° in extension and $2.2^{\circ}/2.3^{\circ}$ in axial rotation left/right (Tables I and V), but the differences were not large (Tables III and VI). The posterior USS fracture

system reduced the ROM in axial rotation left/right with $3.9^{\circ}/4.3^{\circ}$, which was distinctly better than the AOFI, with $4.8^{\circ}/5.7^{\circ}$. In extension, the difference in ROM between the USS fracture system and the AOFI was small (Table III).

All anterior fixation systems with the interbody graft reduced the ROM in flexion (1.8° to 4.5°) and lateral bending (2.7° to 5.2°) to less than that of the intact spine

Table III. p values (● <0.05; – >0.05) resulting from the Wilcoxon signed-rank test for unpaired groups, comparing ROM of anterior, posterior and combined fixation systems in flexion/extension. The adjusted level of significance is very small because of the large number of comparisons. This Table indicates only the relative strength of the comparison

	Flexion		USS fract. system	AOFI int	Kan CI	Kan SR	V-Fix SC/SR	V-Fix SC/DR	Kan CI + AOFI	Kan SR + AOFI	V-Fix SC/SR + AOFI	V-Fix SC/DR + AOFI
	Intact	Extension										
Intact			●	●	●	●	●	●	●	●	●	●
USS fracture system	–			–	–	–	●	●	●	●	●	●
AOFI	–		–		–	–	●	–	–	●	●	–
Kaneda CI	●		●	–	–	–	●	●	●	●	●	●
Kaneda SR	●		●	●	–	–	●	●	–	–	–	–
VentroFix SC/SR	–		–	–	●	●	–	–	●	●	●	●
VentroFix SC/DR	–		–	–	●	●	–	–	●	●	●	●
Kaneda CI + AOFI	●		●	●	●	–	●	●	–	–	–	–
Kaneda SR + AOFI	●		●	●	●	–	●	●	–	–	●	–
VentroFix SC/SR + AOFI	●		●	●	●	–	●	●	–	–	–	–
VentroFix SC/DR + AOFI	●		●	●	●	–	●	●	–	–	–	–

Table IV. p values (● <0.05; – >0.05) resulting from Wilcoxon signed-rank test for unpaired groups, comparing the ROM of anterior, posterior and combined fixation systems in right/left lateral bending. The adjusted level of significance is very small because of the large number of comparisons. This Table indicates only the relative strength of the comparison

Lateral bending	Right		USS fract. system	Fix Int	Kan CI	Kan SR	V-Fix SC/SR	V-Fix SC/DR	Kan CI + AOFI	Kan SR + AOFI	V-Fix SC/SR + AOFI	V-Fix SC/DR + AOFI
	Left	Intact										
Intact			●	●	●	●	●	●	●	●	●	●
USS fracture system	●			–	●	–	●	●	●	●	●	●
AOFI	●		–		●	–	●	●	●	●	–	–
Kaneda CI	●		●	●	–	–	–	●	●	●	●	●
Kaneda SR	●		●	●	●	–	–	●	●	●	●	●
VentroFix SC/SR	●		●	●	–	–	–	●	●	●	●	●
VentroFix SC/DR	●		●	●	–	–	–	●	●	●	●	●
Kaneda CI + AOFI	●		●	●	●	●	●	–	–	–	●	–
Kaneda SR + AOFI	●		●	●	●	●	●	–	–	–	●	–
VentroFix SC/SR + AOFI	●		–	●	●	●	●	–	–	–	–	–
VentroFix SC/DR + AOFI	●		–	–	●	●	●	–	–	–	–	–

(Tables III and IV). In flexion, both Kaneda systems restricted motion with 1.8° and 1.9° which was distinctly better than the VentroFix SC/SR (4.5°) and VentroFix SC/DR (3.2°) (Table III). In lateral bending we observed only one difference between the Kaneda systems and the VentroFix (Table IV). In extension, the Kaneda systems (1.8°/2.0°) were the only devices which kept the ROM below the value for the intact spine, which was 2.8°. Again the differences between the Kaneda systems and the VentroFix were marked. In axial rotation left/right, the anterior systems restricted motion from 2.6° to 5.1° (Table V) and did not reduce ROM below the intact spine which was 2.3°/2.2°. The Kaneda systems reduced axial rotation, with 2.6° to 3.8°, which was distinctly better than the VentroFix, with 4.1° to 5.1° (Table IV).

All anteroposterior combinations with an interbody graft reduced motion in all directions below the ROM of the

Table V. Biomechanical properties of calf spines (T12 to L1) with posterior, anterior and combined spinal fixation systems for left/right axial rotation (degrees)

Moment+7.5 Nm	Axial rotation right		Axial rotation left	
	Median	Range	Median	Range
Intact	2.2	1.9 to 3.6	2.3	1.7 to 3.1
USS fracture system	4.3	3.4 to 5.0	3.9	3.0 to 4.4
AOFI	5.7	4.3 to 7.4	4.8	3.3 to 7.0
Kaneda Classic	3.8	2.7 to 3.8	3.0	2.5 to 3.8
Kaneda SR	2.7	2.2 to 3.2	2.6	2.1 to 3.3
VentroFix SC/SR	5.1	3.8 to 5.4	4.3	3.5 to 5.0
VentroFix SC/DR	4.1	3.3 to 6.1	4.1	2.8 to 4.5
Kaneda Classic + AOFI	1.4	1.2 to 1.6	1.4	1.2 to 1.6
Kaneda SR + AOFI	1.3	1.0 to 1.4	1.2	1.1 to 1.4
VentroFix SC/SR+ AOFI	1.9	1.4 to 2.2	1.8	1.4 to 2.2
VentroFix SC/DR+ AOFI	1.7	1.2 to 2.0	1.7	1.2 to 1.9

Table VI. p values (● <0.05; – >0.05) resulting from Wilcoxon signed-rank test for unpaired groups, comparing the ROM of anterior, posterior and combined fixation systems in left/right axial rotation. The adjusted level of significance is very small because of the large number of comparisons. This Table indicates only the relative strength of the comparison

Axial rotation	Left Right	Intact	USS fract. system	Fix Int	Kan CI	Kan SR	V-Fix SC/SR	V-Fix SC/DR	Kan CI + AOFI	Kan SR + AOFI	V-Fix SC/SR + AOFI	V-Fix SC/DR + AOFI
Intact			–	–	–	–	–	–	●	●	●	●
USS fracture system		–		●	–	●	–	–	●	●	●	●
AOFI		–	●		–	●	–	●	●	●	●	●
Kaneda CI		–	–	–		●	–	–	●	●	●	●
Kaneda SR		–	●	●	●		●	●	●	●	●	●
VentroFix SC/SR		●	●	–	●	●		–	●	●	●	●
VentroFix SC/DR		–	–	●	–	●	●		●	●	●	●
Kaneda CI + AOFI		●	●	●	●	●	●			–	●	–
Kaneda SR + AOFI		●	●	●	●	●	●	●	–		●	●
VentroFix SC/SR+ AOFI		●	●	●	●	●	●	●	–	–		●
VentroFix SC/DR+ AOFI		●	●	●	●	●	●	●	–	–	–	

intact spine (Tables III and IV). Combined anteroposterior fixation restricted ROM in flexion/extension with 0.2° to 0.4° better than each single anterior or posterior fixation system. The differences were considerable with the exception of the Kaneda SR (1.8°) and the AOFI ($0.4^\circ/3.3^\circ$). In axial rotation, the combined fixation provided better stability than any of the single systems (Table VI). In lateral bending the combinations reduced motion more than all anterior systems (Table IV). Combined anteroposterior fixation provided better stabilisation than the posterior systems, but the differences were not always clear.

Discussion

Our aim was to investigate whether the biomechanical performance of combined anteroposterior fixation is superior to that of single anterior or posterior stabilisation.

We found definite differences between the anterior, posterior and combined fixation systems. In all loading directions combined anteroposterior fixation provided better stabilisation than single fixation. In almost all cases, the difference was considerable (Tables III, IV and VI). The only exceptions were the Kaneda SR System in flexion/extension, the AOFI in flexion and lateral bending, and the posterior USS fracture system in left lateral bending.

The enhanced stability of combined anteroposterior fixation was because in each loading direction one implant supported one side of the spine and the other device restricted further stretching of the opposite side. To our knowledge this is the first biomechanical study which gives data on anteroposterior combinations of rigid modern thoracolumbar fixation systems. Clinically, severe destruction of a vertebral body or gross fracture-dislocation is an indication for combined anteroposterior fixation.^{1,9,10} Our biomechanical findings confirm this.

The posterior pedicle-rod fixation systems gave excellent stability in flexion and lateral bending but not in extension

and axial rotation. This stability depended on an interbody graft as a load-bearing anterior column. In flexion this graft resisted movement of the anterior part of the spine whilst the posterior fixation system stopped further stretching of the posterior elements. Conversely, in extension the spine tended to open up at the interbody space and no resistance was provided by structures other than the implant itself. Motion in extension was restricted only by the bending stiffness of the implant and was therefore greater than in flexion. The relative motion or ROM of the injured and stabilised spine compared with the ROM of the intact spine in flexion/extension (Fig. 3) demonstrated these biomechanical actions.

The high stability provided by the posterior pedicle-rod fixation systems in lateral bending (Fig. 4) was due to a similar biomechanical action. In right lateral bending, compression of the right side of the spine was resisted by the right implant rod and the interbody graft. Simultaneously, the left implant rod acted as a tension band and restricted stretching of the left side of the spine. Lateral shifting of the upper vertebrae with parallel rods was resisted by non-parallel placement of the transpedicular screws.¹²

In axial rotation, the spine could not rest on the implant or on the interbody graft. Movement was restricted only by the torsional stiffness of the implant. This resulted in relatively poor stability of the spine stabilised by pedicle-rod systems, as demonstrated in Figure 5.

Several investigators have previously tested the AOFI. The experimental protocol used in these studies has varied substantially regarding the model of the spine, the spinal segments, the model of the injury, the use of transverse connectors, and loading conditions. Some have reported data using individually developed parameters making their results difficult to compare with others. These include flexibility coefficients²⁰ and normalised stiffness.²¹ In order to make comparison easier we calculated the relative ROM as shown in Figures 3 to 5.

Fig. 3

Relative ROM (median and ranges) with respect to the intact state (100%) of T12 to L1 calf spines stabilised with anterior, posterior and combined fixation systems for flexion/extension moments of 7.5 Nm.

Fig. 4

Relative ROM (median and ranges) with respect to the intact state (100%) of T12 to L1 calf spines stabilised with anterior, posterior and combined fixation systems for right/left lateral bending moments of 7.5 Nm.

Panjabi et al²² tested the AOFI monosegmentally at the L5 to S1 segment. They destabilised human spines by transecting the posterior elements and removing parts of the intervertebral disc including the nucleus pulposus. They reported load-deformation curves up to 10 Nm. From their

results we measured relative motion at 7.5 Nm of about 25% in flexion and 95% in extension. This compares fairly well with our findings with a relative motion of 7% in flexion and 117% in extension, as shown in Figure 3. In axial rotation, the results of Panjabi et al differ considerably

Fig. 5

Relative ROM (median and ranges) with respect to the intact state (100%) of T12 to L1 calf spines stabilised with anterior, posterior and combined fixation systems for left/right axial rotation moments of 7.5 Nm.

from our findings (Fig. 5). This may be due partly to our bisegmental fixation since Panjabi et al instrumented only one segment. In lateral bending, they reported a relative ROM of about 35% (Fig. 4). The difference from our findings, of a relative ROM of 11%, may be due to the different testing protocol, especially the lack of an intervertebral spacer.

Nolte et al²³ tested the AOFI bisegmentally on human lumbar spines. They removed the L3 vertebra but did not implant an interbody graft. The reported data consisted of summarised flexion/extension, left/right axial rotation and right/left lateral bending at 7.5 Nm. We used these data to calculate the relative ROM and found similarities to our study in extension and lateral bending (Fig. 4). The ROM in axial rotation reported by Nolte et al was close to the motion of the intact spine (Fig. 5). As explained above, an interbody graft can strongly restrict motion in flexion. Therefore, the large ROM found by Nolte et al in flexion is probably due to the lack of an intervertebral graft.

The USS is a relatively new implant. To our knowledge this is the first experiment providing biomechanical data on it and therefore these findings cannot be compared with those of other studies.

Anterior two-rod fixation systems provided relative stability in flexion and lateral bending but not in extension and axial rotation. With all anterior fixation systems the ROM in right lateral bending was less than in left lateral bending (Fig. 4). This was because the anterior implants were mounted on the right side of the spine on the interbody graft. The fixation system on the anterolateral left side acted as a tension band and restricted further stretching of

that side of the spine. A similar biomechanical mechanism takes place in flexion but not in extension. The resulting relative range of motion in flexion/extension shown in Figure 3 represents this action. In axial rotation none of the anterior fixation systems could restore motion below the ROM of the intact spine (Fig. 5), which might be critical for bony fusion. In this loading condition, the interbody graft did not provide additional support for the injured spine. Motion was restricted only by the torsional stiffness of the implant.

Under all loading conditions, the Kaneda systems stabilised the spine better than the Ventrifix constructs, based on the Ventrifix Single Clamps (SC/SR). The commonly used, more stable Ventrifix double rod construct with Ventrifix double rod clamps was not included in the current study.

One reason for the different biomechanical performance could be the vertebra-screw interface. We had to reuse the same screw holes of the Kaneda systems for the Ventrifix systems. An increasing screw diameter provides a higher screw fixation strength,²⁴ however, provided that no bony microcracks occurred in the environment of the screws because of previous testing. The inner (5.0 mm) and outer (7.5 mm) diameters of the Ventrifix screws were greater than those of the Kaneda systems (Kaneda Classic 3.9 mm/6.0 mm, Kaneda SR 4.5 mm/6.25 mm). To avoid this uncertainty in future experiments, the strength of screw fixation should be controlled by measuring the insertion torque, as this correlates with the strength of the fixation.²⁵

Different designs of implant seemed to produce different

biomechanical performances. The use of a different screw-locking technique with the Kaneda SR system provided better stability than the older technique of the Kaneda Classic system (Figs 3 to 5). The better mechanical behaviour of the Kaneda systems in general, in comparison with the Ventrifix SC/DR construct, may be explained by the number of transverse connectors and by the connection between rod and bone. Various studies show that transverse connectors add stability to anterior spinal fixation systems.^{4,26,27} While the Kaneda SR and the Kaneda Classic system were equipped with two transverse connectors, the Ventrifix (SC/DR) had only one. The Ventrifix SC/SR construct is mainly used in the thoracic area of the spine; in the lumbar region the double-rod construct is recommended, since it gives higher stability. The number of longitudinal rods also influences the biomechanical performance of anterior fixation systems. The use of two rods for better biomechanical performance has been described previously.^{16,28} The better biomechanical performance of the Ventrifix SC/DR with two rods compared with the Ventrifix SC/SR with one rod in our study (Figs 4 and 5), confirms this theory.

The Kaneda system has previously been subjected to frequent biomechanical testing. The experimental protocol used in these studies has varied greatly regarding the model of the spine, spinal segments, the model of the injury, the number of transverse connectors and loading conditions. In some studies it is uncertain whether the Kaneda CI system or the Kaneda SR system was used. We compared our findings on relative motion with those reported by other investigators.^{1,10,26,29-32} Under all loading conditions, the relative movement in our study was slightly above that calculated by others (Figs 3 to 5). In all studies, including ours, the different loading conditions produced similar tendencies showing high biomechanical stability of the Kaneda system in flexion and lateral bending and good stability in extension. In all studies, the greatest relative movement was reported in axial rotation (Fig. 5). Variability in the results of the various studies is probably due to the different testing protocols.

The findings on the anterior Ventrifix also cannot be compared with other studies since this is the first experiment providing data about this implant.

Several limitations of our study should be noted. First, it was performed on calf spines and human spines are obviously a more valid model. We chose the calf spine because human spines are hard to obtain and generally are available only in the older age group, with considerable scatter in bone mineral density and disc degeneration. This variability strongly affects the biomechanical characteristics of these spines. This results in high standard deviations and low significance of the data obtained. Furthermore, human spines carry the potential risk of infection for the researcher and ethical questions have to be considered. By contrast, calf spines are easily available in a large quantity and consistent quality. The bone mineral density of calf verte-

brae is similar to young human vertebrae³³ and ensures a strong screw fixation, which is a prerequisite for sequential testing. Additionally, the biomechanical properties of 12 to 16-week-old calf spines were shown to be similar to those of human spines.^{34,35}

We created an unstable spine model by removing the vertebral body of T13 (the calf has 13 thoracic vertebrae) and the adjacent discs. In terms of the three-column spine,³⁶ this represents a two-column-instability which in clinical terms correlates with AO-A3.3 burst fractures.³⁷ These burst fractures can be created experimentally, but the type of fracture can vary considerably.^{21,38} Although an experimentally produced fracture seemed to be more 'physiological' we relied on resecting the T13 vertebra for greater standardisation. Furthermore, this model is clinically valid since it represents a vertebrectomy used in the clinical management of burst fractures,⁹ tumour resection³⁹ or post-traumatic kyphosis.⁴⁰ The wooden block represents the bone graft used after removal of a vertebral body.⁴¹ The graft was compressed in the defect to simulate the in vivo interbody grafting technique. A systematic error could have been introduced by re-using the same screw holes for the anterior fixation systems, but the design of the study required testing in the same order and we attached the fixation systems according to the manufacturer's instructions, with defined insertion torques using torque wrenches.

This implant test was performed without axial preload and muscle forces, and thus cannot strictly be considered to be physiological. The true loading conditions are not known and therefore different research groups use their own loading parameters. We chose loading conditions with pure moments of up to 7.5 Nm often used by other investigators and suggested for biomechanical in vitro testing of spinal implants.^{19,42-44}

Given these limitations in the model used in our study, we were able to distinguish differences in the performance of various anterior, posterior and combined fixation systems under standardised conditions. These results provide an important basis for discussing the method of stabilisation of the severely injured spine.

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