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A universal spine tester for in vitro experiments with muscle force simulation

H.-J. Wilke, L. Claes, H. Schmitt, and S. Wolf

Abteilung für Unfallchirurgische Forschung und Biomechanik, Universität Ulm, Ulm, Germany

Summary. We report a new apparatus to determine the quasistatic, three-dimensional, load-displacement characteristics of spines including muscle forces. The loading frame can be adapted to mono- and polysegmental specimens from the lumbar or cervical spine as well as to entire spines. Three force and three moment components can be applied in either direction individually or in combination with no constraint on the resulting motion; the loads can be applied at user-chosen rates of application and release with continuous recording of displacements, so as to study either creep or relaxation. The loads and displacement-measuring devices are computer-controlled. Thus, this testing device provides a tool for many kinds of stability tests and for basic research of spine biomechanics. A first experiment shows that the application of muscle forces significantly affects the load-deformation characteristics and intradiscal pressure.

Key words: Biomechanics – Spine tester – Spinal stability – Muscle simulation

The past few years have seen an explosion in the numbers of new devices of spinal fixation for the reconstruction of spinal injuries, damage of the intervertebral discs, correction of deformities, and tumor surgery. These new implants together with new surgical procedures should be evaluated biomechanically in vitro prior to clinical use to determine actue stability and to compare them with clinically accepted means of fixation. In vitro investigations can also provide basic information about load distribution in the different spinal elements, such as ligaments, intervertebral discs, or the facets of the intervertebral joints. Such information may provide insight into the mechanical causes of low-back pain. Such tests, however, require suitable experimental devices to impose physiologically reasonable loads under standardized conditions.

Most reported in vitro experiments have been conducted in special devices mounted in available material-testing machines [2, 21, 22, 25, 26]. Under such test conditions, either load applications or motions or both are often constrained. In many of these experiments, physiological loading conditions were impossible. Often the axial preload was neglected, although it greatly affects the deformation characteristics [17]. Most authors also neglect mucles forces: only two reports describe the simulation of single muscle forces in in vitro experiments [5, 19]. Both authors described a strong influence on the results by these additional forces. In addition, each loading condition often required a different experimental set-up. The loads could only be applied separately, not in combination and not in either direction. Furthermore, the measuring transducers usually had to be adjusted again in the new set-up, leading to potential errors in comparing data between experiments.

For these reasons, a universal spine tester for quasistatic moments was designed which would fulfill the following requirements:

1. The spine tester should allow the fixation and testing of specimens from all spine regions: mono- or polysegmental specimens from the lumbar or cervical spine, as well as entire spines.
2. The specimens must be able to move unconstrained in all six degrees of freedom (Fig. 1).
3. All six load components (flexion/extension, lateral bending right/left, axial rotation left/right, left and right shear, anterior and posterior shear, axial compression or decompression) should be applicable without any manipulation of the specimen.
4. Any load combination should be possible.
5. The loads should be applicable continuously or stepwise.
6. The specimens should be loaded with changing loads, e.g., flexion-extension-flexion and so on.
7. Muscle forces should be simulated.

Method

The spine tester consists of a base mount with a traveling gantry (Fig. 2). The height of this portal can be adapted to a specimen of length up to 800 mm. Thus, mono- and polysegmental specimens as well as entire spines can be mounted in this testing device. The size of the entire machine is 700 × 1000 × 2000 mm (width × length × height).

Correspondence to: H.-J. Wilke, Abteilung für Unfallchirurgische Forschung und Biomechanik, Universität Ulm, Helmholtzstrasse 14, D-89081 Ulm, Germany

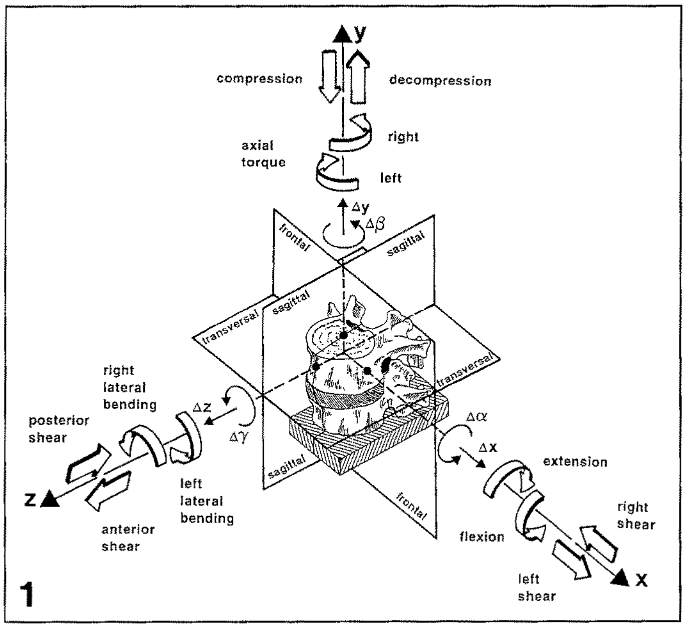

Fig. 1. Three-dimensional coordinate system placed in the center of the upper vertebral body. All possible load and motion components are illustrated. The *arrows* of the motion components $\Delta\alpha$, $\Delta\beta$, $\Delta\gamma$, Δx, Δy, Δz represent the positive direction. (This figure is adapted from [24] with permission)

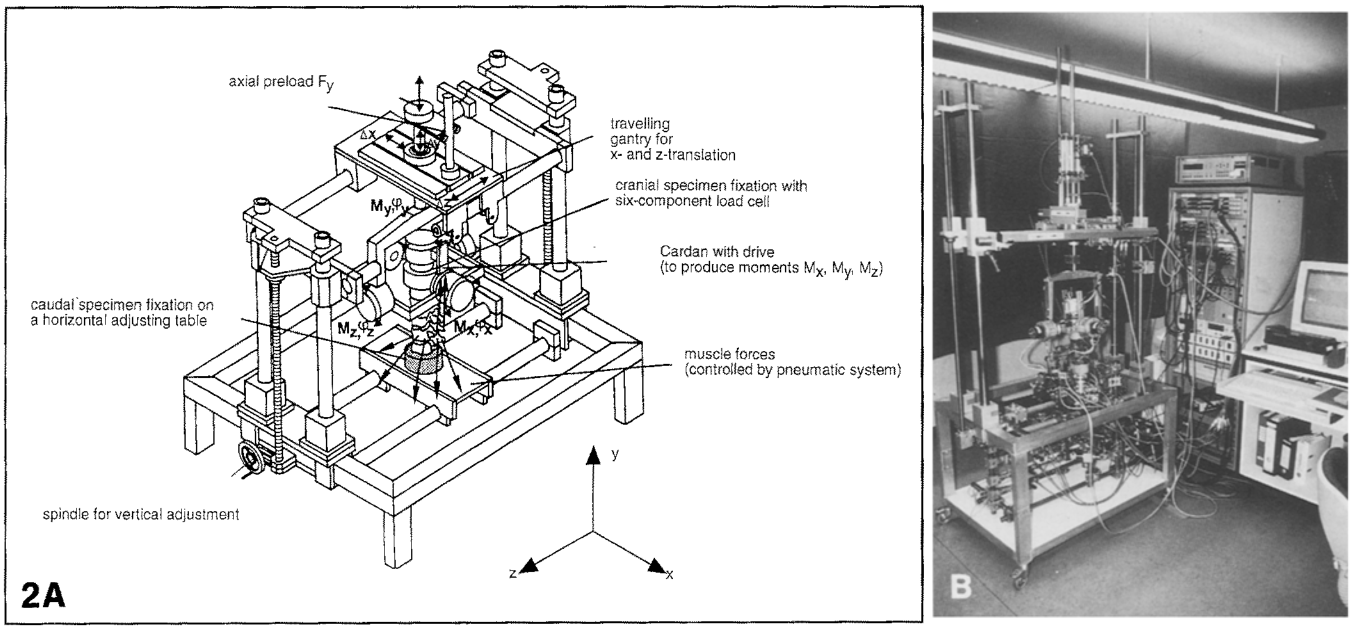

Fig. 2. A Schematic diagram of the spine tester. **B** Photograph of the spine tester with electronics and computer

The core part of this spine tester is the mounting device for the specimen. In most tests, the caudal part will be fixed on the adjustable horizontal mounting table; if necessary, it can also be mounted in a second gimbal. The cranial part is fixed in a specially designed gimbal (cardan joint). This gimbal allows rotation around all three axes and is able to move up and down in a vertical (y) direction. This entire system moves with a traveling gantry in the anterior-posterior (z) direction. A second slide, which is integrated in the mean slide, enables this entire system to move in the medial-lateral (x) direction. Thus, the spine can move in all six degrees of freedom. Each degree of freedom can be constrained or released individually or in combination. The top slide provides a maximum translation Δx up to 225 mm for lateral translation, an axial translation Δy up to 250 mm, and an anterior or posterior translation up to 750 mm. The gimbal allows a lateral rotation φz up to ± 90°, any axial rotation φy, and a flexion/extension angle φx up to ± 45°. All these maximum motions are possible at the same time. Thus, short and medium polysegmental specimens can be loaded and tested under all loading conditions, without moving or turning it. However, if the range of motion is larger in one direction (e.g., if the lateral translation Δx is larger with lateral bending), the specimen can be turned 90° so that the main motion moves in the longitudinal z-direction of the spine tester. By turning the gimbal 90° around the vertical y-axis, the flexion-extension angle can go up to ± 90°. Roller bearings insure low friction in all six degrees of freedom.

The translations Δx, Δz of the top slide as well as the axial motion of the entire specimen (Δy) are measured by contactless displacement transducers (Balluff, Neuhausen/Fildern, Germany) with a resolution of 0.025 mm. This contractless measuring system was chosen in order to keep friction of the entire testing device as low as possible.

The rotations φx, φy, φz of the cranial end of the specimen are transduced directly from rotatory variable displacement transducers (RVDT, Novotechnik, Ostfildern, Germany) in the three gimbal axes. The measurements are input into an AD-converter and the computer.

All displacements occur through stepper motors and a pneumatic system. Pure moments, i.e., flexion/extension moments (± Mx), axial torque left/right (± My), and lateral bending moments right/left (± Mz) are introduced directly in the gimbal. Choosing this design of the gimbal with integrated motors, continuous and

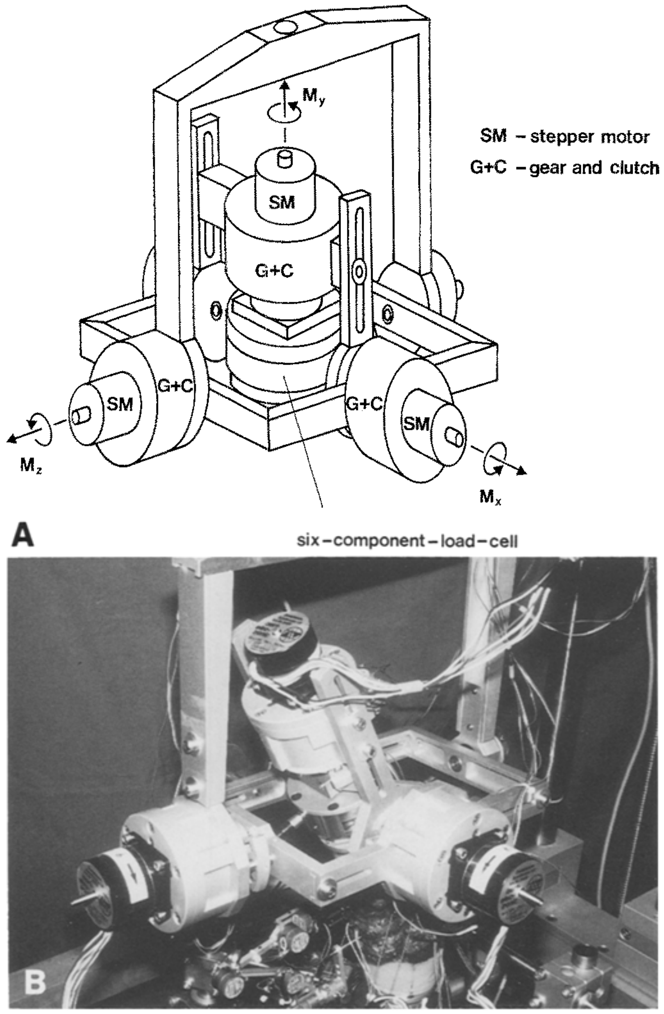

Fig. 3. A Schematic diagram of the gimbal for external moments with stepper motor *(SM)* and gear and clutch *(G+C)* in each axis. The six-component load cell is adjusted in the center of the three axis. **B** Photograph of the gimbal with drive

changing loading cycles are possible (Figs. 3 and 5). A stepper motor with a torque of 55 Ncm and 1.8° per step is connected to each of the three axes. Harmonic drive gears (Harmonic Drive, Limburg/Lahn, Germany) with a ratio of 1:160 increase the moment up to 50 Nm. The motors then flex, bend, or torque the specimens with about one-ninetieth of one angular degree. Each motor can be connected with a clutch to its gimbal axis and can constrain or allow free motion in the corresponding degree of freedom. If only one motor is clutched, a pure moment around this axis occurs. The other two axes allow a free rotation. In order to compensate for the moment from the motors, gears, and clutches, their weight is balanced on the opposite side.

The total weight of the gimbal with drive and compensation weights is about 7 kg and acts, unless compensated, as an axial preload on the specimen. In order to reduce this preload or to apply additionally a controlled preload, two parallel pneumatic cylinders can compress or decompress the specimens or can compensate for the preload. The apparatus can apply an axial preload up to 1000 N.

Shear forces in the anterior-posterior or lateral directions can be applied with additional stepper motors. Cables can be attached at the top slide or directly to the specimen, then guided with pulleys, and rolled up or off from a special spindle. The forces are measured by load cells (Burster, Germsbach, Germany) fixed between the cables.

A six-component load cell (Schunk, Lauffen/Neckar, Germany) measures the introduced moments M*x*, M*y*, M*z*, and the shear componets F*x*, F*z*, and the axial force F*y*. The single load components can be fed to the computer directly from the amplifier either digitally by the RS-232 interface or by the AD-converter. The computer transfers them by a coordinate transformation into the coordinate system of the spine (Fig. 1). The measuring range of this load cell is for the forces F*x*, F*z* = 500 N and F*y* = 1500 N, and the moments M*x*, M*y*, M*z* = 40 Nm. This load cell can also be fixed at the caudal adjusting table, and then it is possible to measure the reaction forces (e.g., directly at the sacrum).

Muscle forces are introduced by cables attached with screws to the insertion points. Each cable represents a user-chosen muscle group. The force in the cables and thus the simulation of the muscle forces are controlled by a pneumatic system, consisting of five pulling cylinders for the muscle forces and two pulling-pressure cyclinders for the axial force. The forces from the cylinders are proportional to air pressure regulated by computer-controlled electronic pressure transformers. The pneumatic cylinders for the muscle force regulation are mounted in the middle sagittal plane. Thus, a symmetrical vector pair with distinct direction can be realized with pulleys. Clamping the cable on one side allows a unilateral muscle force. The arrangement of the muscle forces can be user-selected depending upon the question or spine region and adapted easily with an assembly of unit parts of rods, clamping devices, and pulleys.

The cables (1.4 mm diameter, consisting of 213 single steel strands; Ahlers, Süssen, Germany) are very flexible, with a plastic envelope to reduce the friction at the pulleys. At the end of each pneumatic cylinder, a load cell measures the applied force for the muscle vector pair. The force signals are registered by the computer with an AD-converter and serve as feedback for controlling the muscle forces.

Load cell with different measuring ranges between ± 100 N and ± 500 N (Burster) are used depending on the muscle group.

The various control and measuring devices communicate with each other by means of the computer across different interfaces (Fig. 4, Table 1). The regulation, control, and measurements are carried out automatically by the computer. The manufacturer's information, including model numbers of the different technical items used in the machine, are given in Table 1.

Before the test, the user is asked by the computer which load combination and muscle forces he or she wishes to simulate. Following this input, the computer controls the entire test, registers the data, calculates and displays the result on the screen, and saves them on disc in a format which can be loaded with a spread sheet program. Thus, manual or interactive input from the user is minimized.

Experiment with simulated muscle forces

In a preliminary experiment, one specimen was tested to determine the influence of muscle forces on the three-dimensional motion characteristics and intradiscal pressure of a single motion segment. For this case, only the flexion/extension test was chosen from the variety of all possible load applications.

The specimen was fresh, frozen, lumbosacral cadaveric spine (L2–S1) of a 56-year-old male donor (56 kg). It was thawed at room temperature, and all musculature was removed while leaving intact all ligaments and bony tissue. The cranial vertebra (L2) and the sacrum were potted in polymethylmethacrylate (Technovit 3040; Heraeus Kulzer, Wehrheim/Ts, Germany). Cables representing five symmetrical pairs of muscle groups were fixed to L4 by screws. A special transducer for intravertebral disc pressure measurements with a diameter of 1.3 mm (type MV 162; Mammendorfer Institut für Physik und Medizin, Hattenhofen, Germany) was inserted into the nucleus pulposus between L4 and L5; the correct position of the transducers was controlled by X-ray (Faxitron, type 43805N; Hewlett Packard, Ore., USA).

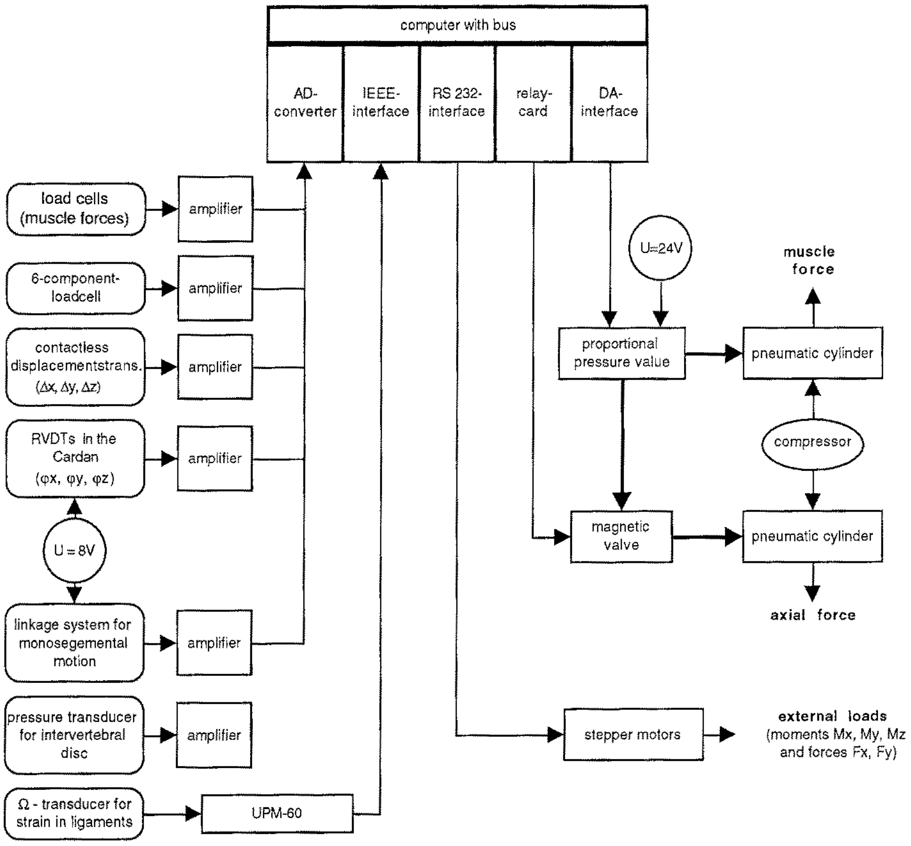

Fig. 4. Diagramm of connection of the entire spine tester

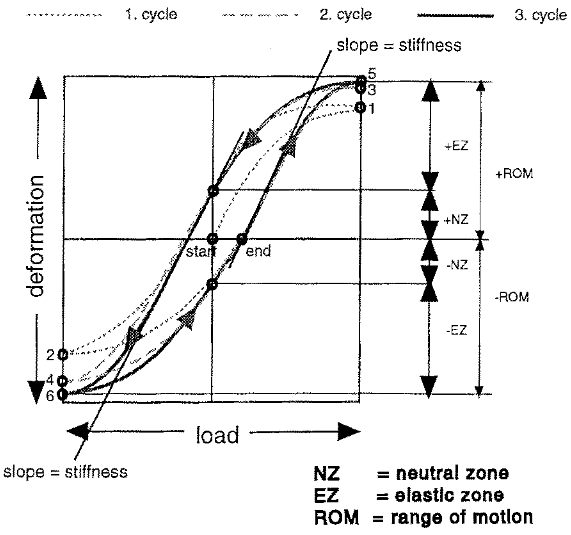

Fig. 5. Typical load-displacement curve with continuously changing load

The specimen was then fixed in the spine tester (Fig. 7). It was kept moist with saline and wrapped in thin food packaging plastic during the entire test. For measurement of the three-dimensional monosegmental motion, a specially developed electrogoniometric linkage system (resolution 0.1 mm for translation components and 0.1° for rotation components) was fixed to L4 and L5 with modified Schanz screws (Fig. 7). The specimen was then tested with pure flexion/extension moments (± *Mx*) in three cycles between 7.5 Nm and –7.5 Nm. These tests were repeated without muscle forces, with each symmetrical muscle vector pair separately (80 N per vector pair), and with all muscle forces in combination (Fig. 6).

Results

Simulated muscle activity influenced strongly the load-deformation characteristics (Fig. 8). The different muscles moved the specimen from the neutral position with a certain offset to another position. Muscle action in most cases increased the stiffness and decreased the neutral zone and the range of motion of the motion segment L4–5. This was more evident for flexion than for extension moments. Without acting muscle forces, the extension stiffness was 0.7 Nm/deg and the flexion stiffness 0.9 Nm/deg. With five pairs of symmetrical muscle forces of 80 N, the stiffness increased approximately an order of magnitude to 15 Nm/deg for both flexion and extension moments. The various muscle groups influenced the motion behavior very differently. Without muscle forces, the load-displacement curve exhibited a sigmoid character, and with all muscle forces, an almost linear relationship. The total neutral zone (± NZ) decreased from 2.5 to 0.25 deg with muscle action, the total range of motion (± ROM) for 7.1 to 0.8 deg with a flexion/extension moment of ± 7.5 Nm.

The load-pressure characteristic of the intradiscal pressure changed substantially (Fig. 9). In neutral position (*Mx* = 0 Nm), the pressure was 0.08 MPa without and 0.45 MPa with all muscle forces. Without muscles as well as with most single muscles, the lowest pressure was around the neutral position. The pressure then increased when the spine was either flexed or extended. With all muscles activated, the pressure during flexion was lower than in the neutral position and monotonically increased to a peak value at maximum extension.

Table 1. Details of components used in the spine tester

	Component	Type	Remark	Company
Drive				
Motors in the Cardan	Stepper motors and controller	isel 3450	55 Ncm	Isert-electronic, Eiterfeld FRG
		isel-CNC-controller C142		Isert-electronic, Eiterfeld FRG
Gear	Harmonic drive gear	HDUF 20/160/BLS	$i = 1:160$	Harmonic-Drive, Limburg/Lahn, FRG
Pneumatic system for muscle forces	Pneumatic valves	MPPE-3-1/4		Festo, Stuttgart, FRG
	Pneumatic cylinders	DSN-16-100-P		Festo, Stuttgart, FRG
	Pneumatic cylinders	DNU-32-100-A-L	Low friction	Festo, Stuttgart, FRG
	Magnetic valve	MFH-5-1/8		Festo, Stuttgart, FRG
Control units	Computer	Atari TT		Atari, Raunheim, FRG
	Bus with	Rhothron bus		Rhothron, Homburg/Saar, FRG
	3 AD-cards		12 bit-16 canal (3 μs)	Rhothron, Homburg/Saar, FRG
	1 DA-card		8 bit- 8 canal	Rhothron, Homburg/Saar, FRG
	IEEE-488 card			Rhothron, Homburg/Saar, FRG
	Relay-multiplexer	UPM 60	60 canals	HBM, Darmstadt, FRG
Measuring devices	Force transducer with amplifier	8460	Tensile/pressure	Burster, Germsbach, FRG
		97215	100 N, 200 N, 500 N	Burster, Germsbach, FRG
	6-component load cell	FT 1500/40	1500 N/40 Nm	Fritz Schunk, Lauffen/Neckar, FRG
	Contactless displacement transducers with amplifier and electronics	BTL″-P1_0225-P-S50	225 mm	Balluff, Neuhausen/Filder, FRG
		BTL″-P1_0750-P-S50	750 mm	Balluff, Neuhausen/Filder, FRG
		BTA-A		Balluff, Neuhausen/Filder, FRG
	RVDTs in the Cardan	P2701-502	Linearity 0.05%	Novotechnik, Ostfildern, FRG
Miscellaneous	Power source	E3610 A		Hewlett Packard, Böblingen, FRG
		E3611 A		Hewlett Packard, Böblingen, FRG

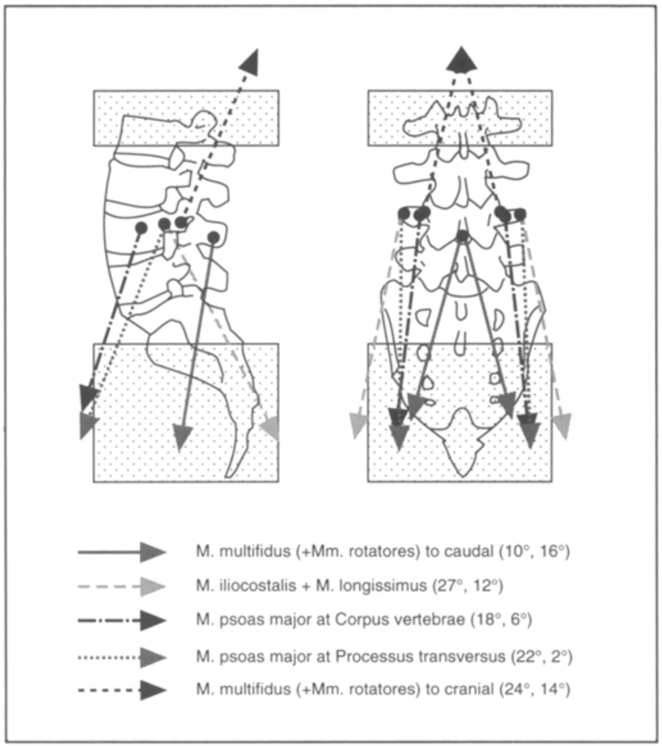

Fig. 6. Schematic diagram for the muscle model representing the most important muscle groups on the lumbar spine. The *starting points* of the vectors show the points of load application. The *angle values* with respect to the vertical axis represent the direction of these muscle vectors (sagittal, frontal)

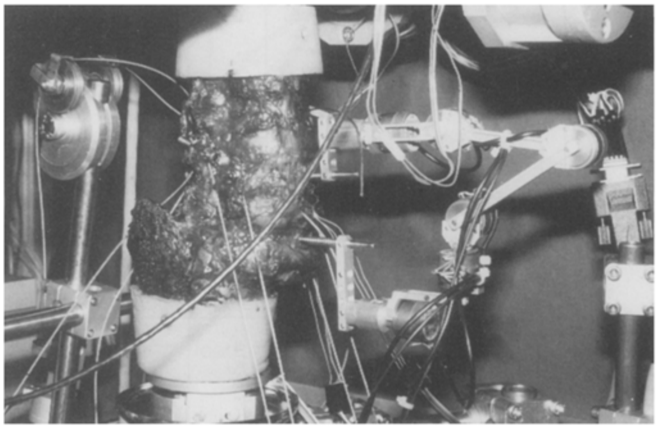

Fig. 7. Lumbosacral specimen fixed in the three-dimensional spine tester. Cables introduce muscle forces. Monosegmental three-dimensional motion between L4–5 is measured by an electrogoniometric linkage system

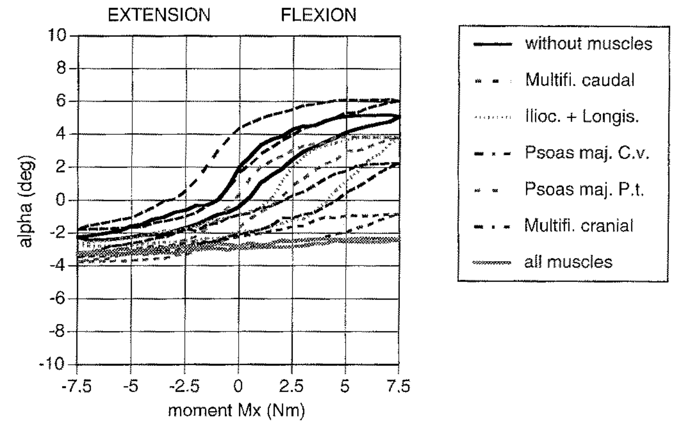

Fig. 8. Load-deformation curves representing the flexion/extension angles of L4–5 over applied flexion/extension moments with respect to different muscle forces. The muscle forces were kept constant at 80 N per vector pair

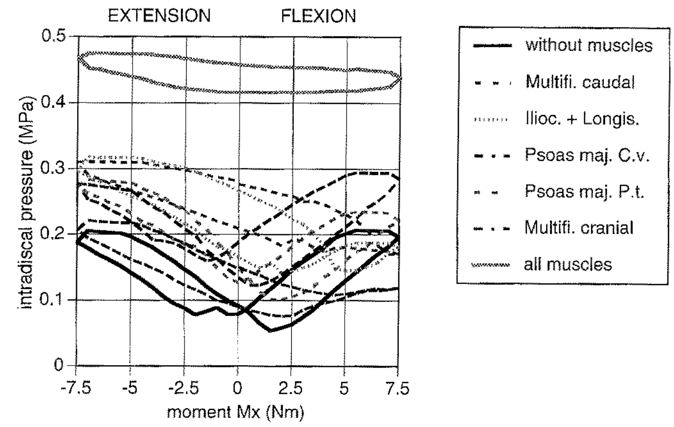

Fig. 9. Intradiscal pressure (L4–5) over applied flexion/extension moments with respect to different muscle forces. The muscle forces were kept constant at 80 N per vector pair

Discussion

The first loading frames were described by Brown et al. [3] and Markolf [8]. Both required different set-ups for different load conditions. The first spine tester that measured the coupled motions of the spine was presented by Panjabi et al. in 1976 [13, 16]. Goel et al. [6, 7] and Panjabi et al. [15–20] tested monosegmental or short polysegmental specimens in special loading frames with pure moments introduced by pulleys. Their loading frames allowed a discontinuous load application either by dead weights or with a pneumatic system. The first spine tester for continuous and discontinuous loading was published by Mickley et al. [9, 10] for monosegmental and short polysegmental specimens. A spine tester for changing loads was described by Wen et al. [23]. None of these devices simulated muscle forces.

This paper introduces a spine tester allowing most kinds of biomechanical, quasi-static, three-dimensional, in vitro investigations with monosegmental or polysegmental or entire spines. In this testing device, muscle forces and external loads can be applied continuously and discontinuously. During the test, the spine can move unconstrained in all directions.

The specimens can be loaded with a speed of up to 2 deg/s, such as might occur in vivo in adjusting one's back in a chair. Thus, this spine tester cannot be used for fast loads as would occur during injury. Although a test could be carried out with about 5000 cycles a day, it cannot practically be used for fatigue tests because the cadaveric material would deteriorate over the long test times.

The spine tester allows the simulation of up to five selected muscle force pairs on the spine (Fig. 6). The five vector pairs representing five symmetrical muscle groups are applied at discrete locations rather than broad insertions. Our preliminary test confirmed a strong influence of muscle simulation as reported by Panjabi et al. [19] and El-Bohy et al. [5] who both applied a single force or force pair at a motion segment. Both motion and intradiscal pressures are very different with muscle activation. In general, the muscles stiffened the motion segment. The intradiscal pressure was higher in flexion than in extension as shown by in vivo measurements by Nachemson [11, 12]. Experiments detailing the influence of the different muscle groups can potentially provide information for the physiotherapy of spine instabilities and back pain. Furthermore, such results could be important as input for mathematical models.

In this experiment, muscle forces were only attached to L4, and their influence was measured on the single segment L4–5. No intersegmental muscle forces were simulated. The muscle forces were kept constant (80 N per vector pair) throughout the tests. We do not know what combination of five muscle force pairs simulate the best in vivo motions. In reality, an obviously more complex muscular apparatus exists. The next step therefore should be to study the motion behavior with respect to a muscle combination using changing forces depending on the kind of motion. This study could be based upon in vivo data. The influence of external loads can then be studied under more realistic conditions.

The spine tester additionally allows continuous as well as stepwise load and unload cycles with changing directions. Reported experiments are generally conducted with stepwise increasing loads [6, 7, 18–20] and periods of 30 s [20] or 2 min [4] to allow relaxation. While stepwise loading is nonphysiologic, it is important to have this capability to compare results of past experiments with experiments with continuous loading at different speeds.

This testing device provides a flexible tool for many kinds of stability tests and for the basic research of spine biomechanics. The strong influence of muscle forces found in our preliminary tests suggests that these forces cannot be ignored when studying spine biomechanics.

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