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Comparison of intradiscal pressures and spinal fixator loads for different body positions and exercises

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Loading of the spine is still not well understood. The most reliable results seemed to come from the intradiscal pressure measurements from studies by Nachemson, 1966. A new similar study by Wilke *et al.* (1999) complemented the present study and confirmed some of the earlier data, although it contradicted others. The new data did not confirm that the load on the spine is higher in sitting compared with standing and did not find distinct differences between positions in which subjects were lying down. The objective of this paper was to compare results from two independent *in vivo* studies (applying different methods) to provide information about spinal loading. In one of these studies (Wilke 1999), intradiscal pressure was measured in one volunteer in different postures and exercises, and in the other study (Rohlmann *et al.* 1994) the loads on an internal spinal fixation device (an implant for stabilising unstable spines) were determined in 10 patients. The absolute values of the results from both studies were normalized and compared for many body positions and dynamic exercises. The relative differences in intradiscal pressure and flexion bending moments in the fixators corresponded in most cases. Both studies showed slightly lower loads for sitting than for standing and comparatively low loads in all lying positions. High loads were measured for jogging, jumping on a trampoline and skipping. Differences between trends for intradiscal pressure and for flexion bending moments in the fixators were found when the load was predominantly carried by the anterior spinal column, as during flexion of the upper part of the body or when lifting and carrying weights. The combination of the results from these two methods may improve the understanding of the biomechanical behaviour of the lumbar spine and may be used to validate models and theories of spinal loading.

1. Introduction

Little information exists about the loads acting on the spine during the different activities of daily living. Spinal geometry is very complex. Therefore, biomechanical models for calculating spinal loads require simplifications and assumptions with often unknown relevance. Direct *in vivo* measurement of complete spinal loading is

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not yet possible. The intradiscal pressure is a measure for the load on the anterior spinal column but gives no information about the loads transferred by the facet joints. Nachemson (1963, 1966, 1981), Nachemson and Morris (1964), Andersson *et al.* (1974, 1977) and others have measured the intradiscal pressure for several activities. Based on these pioneering measurements, many recommendations are given to patients with back problems. More recent studies using different direct and indirect techniques to quantify the spinal load, however, find contradictory results for some activities, which calls into question the basis for these recommendations. For example, the measured disc pressures in the earlier studies were higher for sitting than standing. Stadiometric studies, however, have shown that body height increases when sitting after standing for a while, indicating a lower load for sitting (Althoff *et al.* 1992). More recently, Wilke *et al.* (1999) measured intradiscal pressure for several dynamic activities with a flexible pressure transducer instead of a stiff needle. They confirmed most of the earlier intradiscal pressure measurements but found different results for some body positions which included sitting and lying on a lateral side. The major limitation of this new study was that it was performed with only one volunteer due to ethical reasons.

A different approach to obtain information about the spinal load during daily activities was introduced by Rohlmann *et al.* (1994). They equipped an internal spinal fixator with load sensors (figure 1) and measured the loads on the implant for many activities (Rohlmann *et al.* 1995, 1997a,b, 1999, 2000a,c). An internal spinal fixator is often used to instrument posteriorly a spine which is unstable due to a traumatic, tumorous or degenerative disorder. During surgery, screws are fixed via the pedicles to the vertebrae and, on both sides of the processus spinosus, longitudinal rods are connected to these screws. In the bridged region, the spinal load is shared by the spinal column and the fixators, and it is not know which part of the load is taken over by the implant. Rohlmann *et al.* (1999, 2000a,c) found that the bending moment is the most important load component in the fixator. The amount of the bending moment was mainly influenced by the indication for surgery (vertebral compression fracture, degenerative instability) and the surgical procedure. Bending moments in the fixators were low when the region bridged by the fixators was compressed during surgery and they were high when it was distracted (Rohlmann *et al.* 1999, 2000a,c). In an upright body position the loads on the fixators were higher than in a lying body position (Rohlmann *et al.* 1999). Among all activities performed regularly, walking caused the highest bending moments in the fixators (Rohlmann *et al.* 1997a). Walking speed had only a slight influence on implant loads. Lifting and carrying a weight with the hands had only a minor effect on the bending moments in the fixators (Rohlmann *et al.* 2000a). Insertion of a bone graft from the iliac crest for anterior interbody fusion had a significant influence on fixator loads (Rohlmann *et al.* 2000b). After anterior interbody fusion, implant loads stayed nearly constant until implant removal (Rohlmann *et al.* 2000c).

There have been no other studies until now which have investigated more activities with the goal of determining the loads acting on the spine. A combination of both the intradiscal pressure measurements and the fixator load measurements therefore is an opportunity to improve the understanding of the biomechanical behaviour of the spine. It also may encourage other groups to develop new theories for those activities for which the *in vivo* measurements delivered other results than theories hitherto predicted.

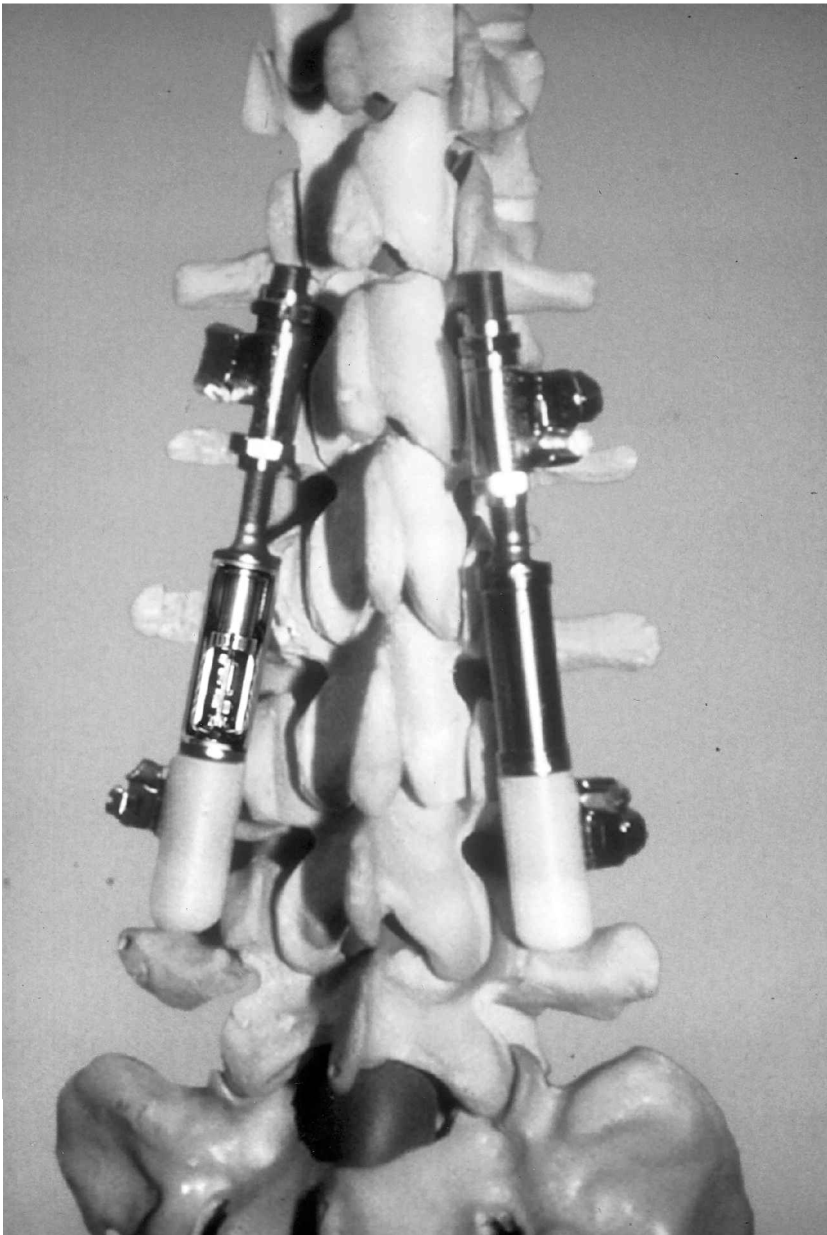

Figure 1. Telemeterized internal spinal fixators mounted on a plastic spine. The left fixator is cut away so that the telemetry unit and coil can be seen.

The aim of this study was therefore to compare *in vivo* results of intradiscal pressure and fixator load measurements for several body positions and exercises, with the subjects standing, sitting, crouching, and lying down. Although some of the data have already been published previously they are repeated in this context for comparison.

2. Materials and Methods

2.1. *Intradiscal pressure measurement*

A flexible pressure transducer with a constant diameter of 1.5 mm (5 French, Mammendorfer Institut für Physik und Medizin GmbH, Hattenhofen, Germany) and advanced technology was inserted under sterile surgery conditions in the nucleus pulposus of a non-degenerated L4–5 disc of a 45-year-old male volunteer weighing 70 kg (Wilke *et al.* 1999, 2000a). The cross-sectional area of the disc was 1800 mm^2. A piezoresistive pressure sensor with a measuring range up to 3.5 MPa (35 bars) was integrated in a 7 mm-long metal tip of the pressure transducer (Wilke *et al.* 1999). This pressure measurement study was approved by the State Ethical Review Board (Landesärztekammer, Baden-Württemberg, Germany). The intradiscal pressure was recorded with a telemetry system over 24 h. Many different situations were studied. Results for some of them have been reported previously. For comparison with fixator loads, many additional activities are presented the first time in this paper. The pressures for all activities were normalized with respect to the pressure in the standing position.

2.2 *Measurement of loads on internal spinal fixators*

2.2.1. *Instrumented fixator*: The bisegmental internal spinal fixation device described by Dick (1989) was modified in order to measure the three force and three moment components acting in each fixator. A measuring cartridge containing six load sensors, a telemetric unit and a coil for the inductive power supply was integrated into the longitudinal rod of the fixator (figure 1). For the measurements, a flat coil and a small antenna were placed on the patient's back to activate the paired spinal implants. During measurements, the patients were videotaped and the load-dependent signals of the telemetries of the left and right fixator were stored on videotape together with the images. The implant loads were calculated from the telemetric signals. A monitor allowed on- and off-line display of implant loads. The instrumented implant, the telemetry and the external equipment have been described in Rohlmann *et al.* (1994) and Graichen *et al.* (1996).

2.2.2. *Patients*: Modified fixators were implanted in 10 patients for clinical reasons. Table 1 provides information on the patients and their surgical procedures. Generally, 2–4 weeks later anterior interbody fusion was performed using autografts from the iliac crest. The instrumented fixators were removed, as normal fixators, on average about 1 year after implantation. The Ethics Committee of the Free University of Berlin had approved implantation of the modified fixators in up to 10 patients. Prior to surgery, the procedure was explained to the patients and they gave written consent to implantation of instrumented internal spinal fixators and subsequent implant load measurements.

2.2.3 *Measurements*: Initial fixator load measurements were made soon after implantation of the fixators and were then repeated about 2 weeks after the second operation. The loads were measured once or twice a week during hospitalization and then about once a month until implant removal. In most cases implant loads were not significantly changed after anterior interbody fusion had occurred (Rohlmann *et al.* 2000c).

Table 1. Details of the 10 patients and their surgical procedures.

Patient:	1	2	3	4	5	6	7	8	9	10
Gender	F	M	F	M	M	M	F	F	F	F
Age (years)	59	34	54	72	36	42	46	62	47	54
Weight (kg)	75	90	66	80	75	81	53	85	48	68
Height (cm)	170	185	162	171	173	164	165	157	160	171
Indication for surgery	degenerative instability	compression fracture (old)	compression fracture	degenerative instability	compression fracture	degenerative instability	compression fracture (old)	compression fracture (old)	compression fracture	compression fracture
Bridged vetebra	L3	L4	L3	L4	T11	L4	T12	L1	L1	T12
Bone grafts	L2/3 and L3/4	L3–L5	L2/L3	L3/4 and L4/5	T10/T11	L3/4 and L4/5	T11/T12	T12–L2	T12/L1	T11/T12

In up to 25 measuring sessions per patient, implant loads were measured for several common activities, including standing, lying in different body positions, sitting, walking, and bending of the upper part of the body in different directions while standing. The average peak values and standard deviations (SD) for the 10 patients were calculated for these positions and exercises. A great part of the results for these body positions and exercises has been published previously (Rohlmann *et al.* 1997a,b, 1999, 2000a). For some other activities such as jumping on a trampoline, skipping, jogging on a treadmill, and crouching on hands and knees, implant loads were measured in only one or a few patients. Therefore, for these exercises, only fixator loads measured in one patient (no. 10) are given. This female patient had a fractured T12 vertebral body and the bisegmental fixator was fixed to the T11 and L1 vertebrae. The upper of the two bridged intervertebral discs was removed while the lower one was left intact. This 54-year-old patient had a well-trained musculature since she had exercised regularly in a fitness centre for many years. Most of the results for the special exercises have not been published previously.

For flexion, extension and lateral bending, the patients were asked to bend the upper part of their body as far as possible without pain. The angle to which the patients bent the upper part of their body was not measured, but certainly it differed strongly from patient to patient. Great intra-individual differences were also sometimes found. Owing to wound pain, most patients bend upper part of their body less in the period shortly after surgery than later. However, peak fixator loads were often not found to occur at the maximum bending angle but at a lower degree of flexion.

2.2.4 *Evaluation of fixator loads*: For nearly all activities, the force components perpendicular to the longitudinal axis of the fixator rod and the torsional moments were small. The axial force component and the bending moment in the sagittal plane (Mb, sag.) are the most important load components. The bending moment in the sagittal plane is always meant in this paper when reference is made to bending moment in the fixator. The axial force component has been found to depend strongly on the level of the bridged vertebral body (Rohlmann *et al.* 2000a,c) while the bending moment in the fixator is influenced by the indication for surgery (vertebral compression fracture, degenerative instability) and the surgical procedure (distraction or compression of the bridge region) (Rohlmann *et al.* 1999, 2000c). Axial loading of the spine bends the pedicle screws and the longitudinal rods of the fixators. Thus the bending moments in the implant reflect the spinal load best. Therefore, only their values are presented in this paper. Indication for surgery and surgical procedure differed in the patients with an instrumented fixator, so that the absolute values of the bending moments have only slight relevance. Therefore, bending moments in the fixators were normalized with respect to those measured when the same patient stood upright.

2.3. *Body positions and activities in both studies*

Intradiscal pressure in the one volunteer and fixator loads in all 10 patients were measured for the following activities:

- Standing.
- Lying in a supine, a prone and a nearly straight but relaxed lateral position.

- Sitting relaxed, sitting erect and actively staightening, sitting on a padded wedge (angle of 9.5°), sitting on a physiotherapy ball (pezzi ball), and sitting on a knee-stool (balance). All seats had a normal height so that the knees were bent at about 90°.
- Walking.
- Flexion and extension of the upper part of the body while standing.
- Carrying a load in the hands while standing.

Intradiscal pressure in the one volunteer and fixator loads in only one patient (no.10) were measured for the following special activities:

- Bouncing on a physiotherapy ball.
- Walking with crutches, walking up and down stairs, jogging on a treadmill.
- Jumping on a trampoline.
- Skipping.
- Crouching on hands and knees.
- Arching and hollowing the back while crouching on hands and knees.
- Body lifting by the arms in a sitting position so that the buttocks did not touch the chair.
- Balancing the straight body on parallel bars so that the feet did not touch the ground.

Normally the experimenters did not specify exactly how an exercise had to be performed by the patients since the whole range of fixator loads for an exercise was of interest. Therefore, the median bending moment in the fixator was taken to represent a typical value.

3. Results

The intradiscal pressure was 0.50 MPa on average for standing. This value was set to 100% and the values for all activities are related to it. The peak values are always meant when pressures or bending moments are given. The results are presented in figures 2 and 3.

3.1. *Intradiscal pressure measured in one volunteer and fixtator loads measured in all 10 patients*

The lowest disc pressure (20%) was found when the person was lying in a supine position (figure 2). Slightly higher pressure values were measured for lying in a prone (22%) and a lateral position (24%). The flexion bending moments in the internal fixator were also lowest for lying positions (figure 2). The average values related to standing were 26% for supine position, 32% for prone position, and 34% for lateral position.

For sitting relaxed without a backrest, the intradiscal pressure was 90% of the value for standing. When sitting erect and actively straightening and extending the back, as often recommended by back schools, intradiscal pressure increased to about 110%. The flexion bending moments in the fixators were also slightly lower for sitting (89%) than for standing. Sitting while consciously straightening the spine let the flexion bending moments in the fixators rise to an average value of 100%. Sitting on a stool with a padded wedge had only a minor effect on intradiscal pressure (86%) compared with relaxed normal sitting. For sitting on a physiotherapy ball or a knee-

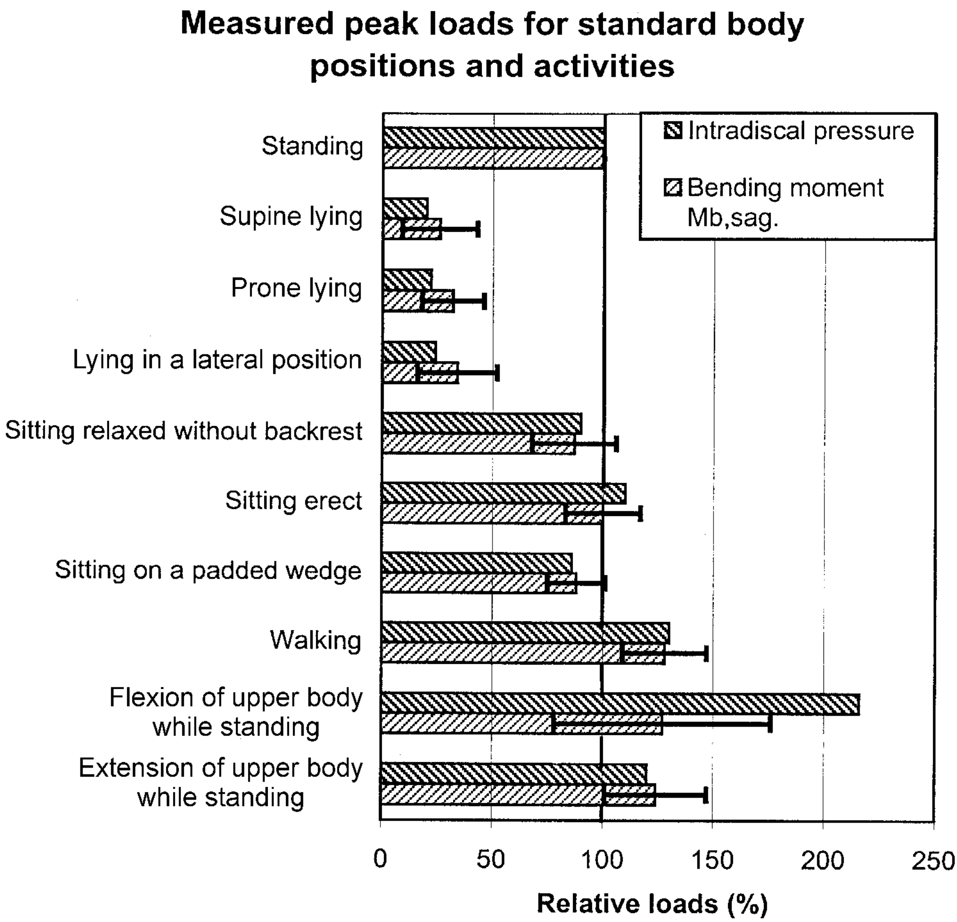

Figure 2. Peak intradiscal pressures (measured in one volunteer) and peak flexion bending moments (mean and SD) in the fixators (measured in all 10 patients) for standard body positions and exercises. The values are given as a percentage of those for standing.

stool (balance) nearly the same intradiscal pressure was measured as for sitting relaxed on a stool. A padded wedge also led to nearly the same fixator loads as sitting relaxed (88%). The type of seating (stool, physiotherapy ball, knee-stool) had only a minor effect on fixator loads. Both intradiscal pressure and fixator load were reduced when leaning against a backrest.

Walking led to intradiscal pressure peaks of up to 130% with a minimum of about 80%. Walking speed had only a slight influence on disc pressure. The flexion bending moments in the fixators were also higher for walking than for standing (on average 128%).

During flexion of the upper part of the body while standing, the pressure in the disc increased almost linearly to 216% for 36° between the thoracolumbar junction and the sacrum (figure 2). For extension a linear increase of the pressure was also measured. However, the maximum value was only 120% at 19°. For flexion, bending moments in the fixators increased less than intradiscal pressure. The difference in the

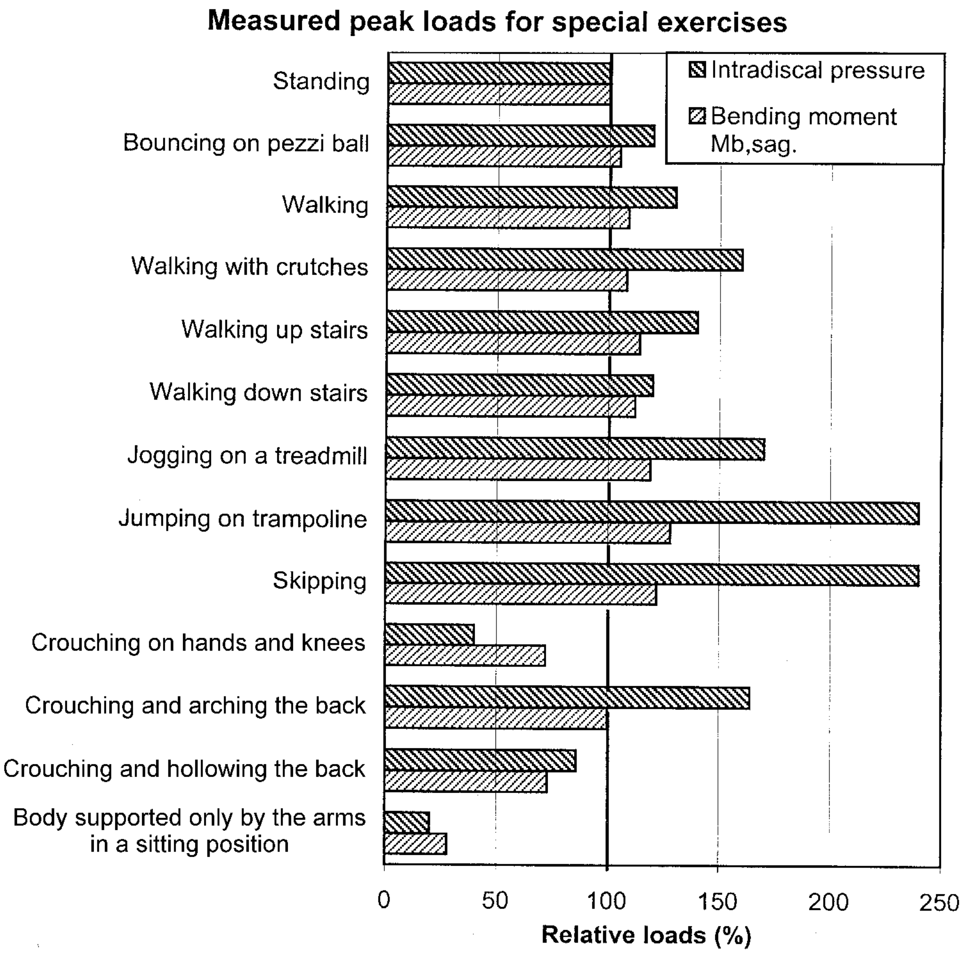

Figure 3. Peak intradiscal pressures (measured in one volunteer) and peak flexion bending moments in the internal fixators (measured in one patient) for special exercises. All values are given as a percentage of those for standing.

increases of the average flexion bending moments in the fixators for flexion (127%) and extension (124%) was small.

Lifting a load with the hands caused the highest intradiscal pressure measured. A maximum 460% was found for lifting a 19.8 kg case. Holding the case close to the body at chest level produced a pressure of 220%, whereas holding it 60 cm away from the chest increased the pressure to 360%. Carrying and lifting a load led to only a slight increase of the fixator loads. The maximum flexion bending moment was mostly lower than that for walking (128%).

3.2. *Intradiscal pressure measured in one volunteer and fixator loads measured in only one patient*

Bouncing on a physiotherapy ball in a sitting position led to an intradiscal pressure between 80 and 120%. In patient 10 the maximum bending moment in the fixators for this exercise was 105% of the value for standing (figure 3).

When the body was supported only by the arms as during body lifting in a sitting position or during balancing the body on parallel bars with the legs in a vertical position, the same intradiscal pressure and nearly the same flexion bending moment in the fixators as lying in a supine position were measured.

During walking, the peak flexion bending moment for patient 10 was 109% of the value for standing. This value was lower than the average value for the 10 patients (128%). When walking with crutches, disc pressures varied between 60 and 160%. The bending moments in the fixators were only slightly influenced by the use of crutches. Climbing stairs led to a maximum pressure in the disc of 140% while for walking down stairs the value was 120%. The peak bending moments in the fixators for walking up and down stairs were 114 and 112%, respectively. Jogging with tennis shoes caused a maximum intradiscal pressure of 170%. The flexion bending moments in the fixators were increased to 119% for patient 10 when jogging on a treadmill at 8 km/h.

Light jumping on a trampoline caused a maximum intradiscal pressure of 240% while the corresponding value for high jumping was 380%. The minimum value during this dynamic exercise was always about 70%. The flexion bending moment of the fixators was increased to 128% while performing light jumping on a trampoline. No corresponding value was obtained for high jumping because the patient was not allowed to do this exercise. The maximum values for light skipping were 240% for the intradiscal pressure and 122% for the bending moments of the fixator.

Crouching on hands and knees (simulating quadrupeds) led to an intradiscal pressure of 40%. Arching the back in this position increased the pressure to 164%, while hollowing the back caused an intradiscal pressure of 86%. The corresponding values for the maximum flexion bending moment in the fixator was 72, 100 and 73%, respectively (figure 3).

4. Discussion

The results provide a comparison of the relative values of intradiscal pressure and fixator loads determined in two independent *in vivo* studies for several body positions and dynamic exercises. With the intradiscal pressure measured in one volunteer, some important differences were found compared with the earlier studies by Nachemson (1966, 1981). The limitation of this new study was that it was only done with the one volunteer. Therefore a comparison with loads acting in an internal spinal fixation device which were measured in up to 10 patients is essential, because few other data exist in the literature and many recommendations are based on findings from intradiscal pressure measurements from the 1960s.

When lying down, the spine does not have to carry the weight of the trunk. Therefore, the intradiscal pressure and the bending moments in the fixators were found to be low. The small differences in the loads for the various lying positions are probably due to slightly different curvatures of the spine.

Slightly lower disc pressure and implant loads were found for sitting than for standing. Nachemson (1966, 1981) reported 40% higher intradiscal pressure values for sitting. The present results contradict this but are in agreement with those of another indirect method for load measurement using stadiometry. Althoff *et al.* (1992) found an increase in body height when the subjects were sitting after standing for a while. This indicates that the spinal load is lower for sitting than for standing. The differences between the results of Wilke *et al.* (1999) and Nachemson (1966) may be explained by the use of different pressure transducers. Nachemson's transducer was integrated in a stiff needle which might have measured artefacts if it was bent due to muscle contraction. The transducer used by Wilke *et al.* could not be bent because the stiff part was only 7 mm long and was inserted completely into the nucleus of the disc where only a hydrostatic pressure is present in case of a non-degenerated disc.

Sitting consciously erect, actively straightening and extending the back, increased the pressure in the disc and the flexion bending moments in the fixators. Higher muscle forces are needed for sitting straight than for sitting relaxed. Higher muscle forces in turn lead to higher spinal loads. The load differences were, however, small and the slightly higher pressure is no argument against sitting erect. Intradiscal pressure and fixator loads were in the medium range during sitting in the different positions. Other unpublished measurements taken by the authors showed that these loads could be reduced greatly when leaning against a backrest since the backrest takes over part of the load. It seems that for low back pain the amount of the global load during sitting is not the crucial factor since the measured loads were lower for sitting than for standing and during walking. However, little information exists about the loads on the facet joints and on the ligaments, which may be high for sitting. For the nutrition of the disc, intersegmental movements are probably very important and people, especially those suffering from low back pain during sitting, are recommended to change their posture frequently. Changing from a lordotic shape of the spine to a kyphotic shape and vice-versa has only a minor influence on spinal load but is probably advantageous for disc nutrition and may reduce low back pain.

When supporting the body only with the hands, as during body lifting in a sitting position or during balancing the body on parallel bars, the spine has to carry not the body weight above, but the body weight below a certain level. This exercise led to nearly the same low pressure and bending moments in the fixators as lying in a supine position. The pulling force on the spine resulting from gravitational force on the body part below the level of interest was obviously compensated by muscle forces.

Dynamic motion, as during walking, jogging, stair climbing, bouncing on a physiotherapy ball, jumping on a trampoline or skipping, led to higher spinal loads than normal standing. However, the loads in these cases were often significantly smaller than for flexion of the upper part of the body or lifting a weight. The impulses on the feet during the dynamic exercises are mainly damped in the foot and knee joint and by the curved shape of the femur and obviously do not reach the spine. Measurements with instrumented hip endoprostheses have shown that such impulses normally do even not reach the hip (Bergmann *et al.* 1995). The dynamic load component at the spine is mainly caused by the accelerations of the upper part of the body. The mass of the upper part of the body moves up and down during these exercises and is therefore responsible for the dynamic component of the spinal load.

Walking with crutches led to higher disc pressure than walking without crutches. However, the volunteer loaded the crutches very 'dynamically'. Implant loads were only briefly reduced when the patients were asked to load the crutches strongly. The use of one crutch often led to higher implant loads than walking without a crutch, since the patients bent the upper part of the body laterally, which increased the load on the ipsilateral fixator (Rohlmann *et al.* 1997a). From these *in vivo* measurements it is concluded that it does not seem necessary for patients with back problems, for example after implantation of spinal fixators, to use crutches when they can walk safely with respect to losing balance.

The load on the trunk is significantly increased during flexion of the upper part of the body as well as when lifting and carrying a weight. These exercises strongly increased intradiscal pressure but had only a minor effect on the flexion bending moments in the fixators. In the region bridged by a fixator, the spinal load is shared by the spine and the implant. Further bending has only a minor influence on the bending of the fixator rods when there is anterior bony support. Therefore activities during bending forward might show lower loads in the fixator compared with the intradiscal pressure. How this load is shared depends mainly on the stiffness of the bridged region. This stiffness depends, among other reasons, on the surgical procedure, the time after surgery, and the weight carried. Spinal stiffness is normally higher in an upright than in a lying body position. This is due to the higher load, which probably leads to a better interlocking of the facets (Wilke *et al.* 1995). If a spinal fixator is fixed to a spinal segment the whole system is stiffer than the fixator itself. In an upright body position, the stiffness of the bridged region is therefore higher than that of the fixator alone. The vertebral bodies are mainly loaded in compression while the fixators are loaded predominantly in bending.

Crouching on hands and knees led to an intradiscal pressure of only 40% of that when standing and a flexion bending moment in the fixator of 72%. This is astonishingly low. Only for lying positions and when the body weight was balanced on the hands were lower disc pressures and lower fixator loads measured. Obviously only low muscle forces are needed for stabilising the back in this position.

Arching and hollowing the back while supporting the body on hands and knees leads to a great deformation of the spine. Hollowing the back caused a pressure increase, but the maximum value for this posture was still less than for standing. The bending moment in the fixators was also lower than for standing. The increase of disc pressure for arching the back was higher than for hollowing the back but lower than during flexion of the upper part of the body while standing. The fixator load for arching was nearly the same as for standing.

The following limitations of these comparisons have to be noted. In principle it would be best to apply both techniques in the same subjects, but ethical reasons did not of course allow this. Intradiscal pressure depends on several factors including disc quality, disc level, body weight and others. Although intradiscal pressure measurements were performed in only one subject, the relative results for standing and sitting are confirmed by published reports of indirect measurements using stadiometry (Althoff *et al.* 1992). Loads on internal spinal fixators depend mainly on indication for surgery (compression fracture, degenerative instability), surgical procedure (distraction or compression of the bridged region), and level of bridged vertebra (Rohlmann *et al.* 1999, 2000a). These factors varied in the patients, but for most body positions and activities the trends in the bending moments for the different exercises were similar for all patients.

Small differences in the relative loads have probably only minor relevance since intradiscal pressure was measured in only one volunteer and fixator loads often in only one patient. For the standard activities measured in 10 patients the standard deviation was relatively large.

5. Concluding Remarks

The idea of making these comparisons came after extensive discussions between the two research groups about their results (Wilke *et al.* 2001b). Although the two studies were completely independent, with the limitations discussed above, surprisingly a very good agreement was found between the results. The data from the two studies even support each other for activities where contradictions are found to earlier studies. Only when the anterior spinal column had to transfer very high loads, as during ventral flexion of the upper part of the body or lifting and carrying weights, did the fixator loads indicate spinal loads which were much too low. The results may be used to confirm models which predict spinal loading, may help to improve knowledge of the biomechanical behaviour of the spine, and will provide many issues for discussion which are especially important for ergonomists.

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