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The stability of bone screws in the os sacrum

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Abstract A variety of points of insertion and implantation techniques are recommended for inserting screws into the os sacrum. On the basis of 16 complete human sacrum specimens the following axial pull-out tests were performed: 1. Insertion of convergent measuring screws, 6.0 mm and 7.0 mm in outside diameter respectively, into the body of vertebra S1 using a monocortical and bicortical technique respectively with perforation of the ventral cortex. 2. Insertion of divergent screws into the ala sacralis at the level of S1 with 6-mm and 7 mm screws respectively, using a monocortical technique without perforation of the ventral cortex. 3. Insertion of convergent 6-mm screws into the body of vertebra S2 using a monocortical and bicortical technique respectively with perforation of the ventral cortex. The highest axial pull-out force was reached using convergent 6-mm screws inserted into the body of vertebra S1 using the bicortical technique with perforation of the ventral cortex (2392.4 N). The use of a 7.0-mm screw in the same implantation technique did not result in higher pull-out forces (2274.7 N).

The monocortical technique reached a pull-out force of 1657.53 N with a 6-mm screw and 1505.64 N with a 7-mm screw. Convergent insertion of 6-mm screws into the body of S2 resulted in pull-out forces of 537.02 N using a bicortical and only 297.71 N using a monocortical technique. Divergent insertion of screws into the ala sacralis reached a maximal pull-out force of 495.47 N using 6-mm screws and 449.79 N using 7-mm screws. These data resulted from a monocortical implantation technique without perforation of the ventral cortex of the ala sacralis. The results of the present biomechanical study show that convergent bicortical implantation in the body of S1 is the most stable technique for screw fixation in the sacrum. The use of 7-mm rather than 6-mm screws did not lead to increased primary stability. Anatomic studies have shown that a safe area exists in the region of the ventral promontory, so this implantation technique appears to be unobjectionable.

Key words Pull-out force · Sacrum · Pedicle screws · Different insertion points

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Introduction

The use of pedicle screws for instrumented spinal fusion, especially for degenerative lumbar and lumbosacral disor-

ders, has markedly increased in recent years. If a normal anatomy is provided, screw insertion into the pedicles of the lower lumbar vertebra usually is unproblematic [4]. While recommendations for screw insertion into the lumbar pedicles of the more unequivocal anatomy do not dif-

fer much, a variety of recommendations have been made regarding the implantation of bone screws in the sacrum on grounds of its special anatomy. Anatomic studies basically show three possible screwing directions: 1. into the body of S1, 2. into the ala sacralis at the S1 level, 3. into the body of S2, [1, 4, 9, 10, 14, 20, 22].

The vast majority of pull-out tests for screws in the sacrum were performed on spinal specimens of people who died fairly late in life. Most specimens originated from pathological institutes, which means that patients may have died after long-term immobilization [5, 15, 21]. In the cited studies the mean age of the specimens was 74 years or older. As lumbosacral instrumented fusion is extremely rare in this age group, the data from these studies cannot be applied to patients undergoing this operation. The specimens in the present study came exclusively from individuals who had died unnaturally without any pre-existing illnesses.

Materials and methods

In the present experimental study on spines of human corpses the stability of different implantation techniques was compared in axial pull-out tests. The influence of the outside diameter of the bone screw was also investigated for 6- and 7-mm-diameter screws. Monocortical insertion was compared to the bicortical technique in the body of both S1 and S2.

Besides the positioning of the screws in both the mono- and the bicortical implantation technique, screw length and outside diameter, as well as bone density, are very important, as shown in other studies [5, 13, 15, 17, 18, 21].

Table 1 Data of all specimens

Specimen	Gender	Age (year)	Weight (kg)	Height (cm)
1	M	35	93	171
2	M	38	75	180
3	M	52	/	/
4	M	59	66	183
5	M	83	63	170
6	M	59	78	173
7	M	75	65	169
8	M	54	73	165
9	M	27	83	178
10	F	54	69	175
11	M	42	81	175
12	M	46	95	187
13	M	39	90	169
14	F	64	81	174
16	M	43	79	171
(n = 14 m; (n = 16) (n = 15) (n = 15)				
2 F)				
Minimum	/	27	63	165
Maximum	/	83	95	187
Mean	/	50.875	78.21	174.57
Standard deviation	/	14.79	10.3	5.93

Specimens

In total 16 complete sacrum specimens were available. They originated from individuals who had died unnaturally at an average age of 51. The ratio between men and women was 14:2 (Table 1).

After extraction the specimens were immediately frozen at -180°C . The bone density was determined in mg/ml calcium hydrogencarbonate (Ca-HA) by Dual Energy Quantitative Computed Tomography (DEQ-CT) in the bodies of vertebrae L1–3 of the same specimen (Table 2). The reason we determined the bone density was that some pull-out forces we compared were not measured in the same specimen. To compare these data the bone densities of the specimens had to follow a normal distribution. We did not investigate the correlation between pull-out force and bone density, because there are many other studies on this topic [11, 13, 15, 18, 23].

Figure 1A and B show the theoretical curves of normal distribution of trabecular and cortical bone densities, which were calculated from the mean and standard deviation. The bone densities of the specimens were integrated into these curves in the shape of perpendicular lines. Both curves show that all bone densities except one cortical density are located within the range of 2 standard deviations above and below the mean. This is the basic requirement in comparing pull-out forces measured in different sacrum specimens.

During the thawing procedure the soft tissues were removed at room temperature.

Implantation techniques

In S1 the following implantation techniques were applied:

1. Inserting a 6-mm screw into the body of S1 with perforation of the ventral cortex

Table 2 Trabecular and cortical bone density for all specimens (L1–L3, in mg Ca-HA/ml)

Specimen	Bone density	
	Trabecular mean	Cortical mean
1	164.6	388.6
2	100.9	345.2
3	156.3	317.5
4	196.7	472.6
5	76.5	211.3
6	97	295.8
7	33.8	279.7
8	97	295.8
9	110.4	267.5
10	133.3	293.8
11	138.5	381.3
12	182.5	459.6
13	75	252.7
14	128.2	319.3
15	111.3	309.2
16	88.6	344
n	(n = 16)	(n = 16)
Minimum	33.8	211.3
Maximum	196.7	472.6
Mean	118.16	327.12
Standard deviation	42.86	70.40

Fig.1 Curve of normal distribution of **A** the trabecular bone densities and **B** the cortical bone densities

2. Inserting a 6-mm screw into the body of S1 without perforation of the ventral cortex
3. Inserting a 7-mm screw into the body of S1 with perforation of the ventral cortex
4. Inserting a 7-mm screw into the body of S1 without perforation of the ventral cortex

The ala sacralis was tested in the following ways:

1. Inserting a 6-mm screw into the ala sacralis at the S1 level without perforation of the ventral cortex
2. Inserting a 7-mm screw into the ala sacralis at the S1 level without perforation of the ventral cortex

The pedicle S2 was tested in the following ways:

1. Inserting a 6-mm screw into the body of S2 with perforation of the ventral cortex
2. Inserting a 6-mm screw into the body of S1 without perforation of the ventral cortex

Figure 2 shows the dorsal insertion points for the three different screw positions. Figure 3 shows the course of the screw axis in S1 in the transverse and sagittal plane. Figure 4 shows the course of the screw in the ala sacralis in the transverse and sagittal plane. Figure 5 shows the screw position in S2 in the sagittal plane.

Fig.2 Posterior view of the sacrum with points of insertion

Fig.3 Direction of the screw axis in S1 in the horizontal and sagittal plane

Screws

Screws with an outside diameter of 6 and 7 mm and an inside diameter of 4 and 5 mm respectively, with a threading of 3 mm per

Fig. 4 Direction of the screw axis in the sacral ala in the horizontal and sagittal plane

Fig. 5 Direction of the screw axis in S2 in the sagittal plane (the screw direction in the horizontal plane is the same as the screw direction in S1)

rotation were used. The threads were self-cutting, and the screws were 150 mm long. Prior to the implantation of the screws the bone-screw interface was prepared with a 3.2-mm drill in the case of the 6-mm screw and a 4-mm drill in the case of the 7-mm screw.

Fig. 6 Spine stress machine with specimen

In order to estimate the stability of the bone-screw connection, pull-out tests axial or at a right angle to the screw are usually performed [5–7, 13, 15, 17, 18, 21, 24]. We measured the pull-out forces in an axial direction, because this is the most exactly defined direction of the screw load.

Holding device

The sacrum was put into a retaining mold made of ultrahard plaster that had a pyramidal shape. In the area of the ventral screw perforation points, pieces of foam-rubber were placed in order to prevent contact between the screw tips and the holding cement.

Testing machine

The pull-out tests were performed with an electronic universal testing machine (Type 14 4 5 0 3, Zwick Ulm; Fig. 6).

Measuring technique

The stress test was performed at a speed of 4.5 mm/min in the direction of the screw axis. The highest force value prior to the fail-

Table 3 Effect of depth of insertion (bicortical vs monocortical) on maximal pull-out force (in Newtons) for three insertion techniques, all using convergent screws

	6-mm screws in S1		7-mm screws in S1		6-mm screws in S2	
	Biocortical (n = 9)	Monocortical (n = 9)	Biocortical (n = 7)	Monocortical (n = 7)	Biocortical (n = 16)	Monocortical (n = 16)
Maximum	3388.2	2455.2	3133.4	2332.3	1249.6	686.4
Minimum	1267.7	370.7	1178.2	617	133.4	59.4
Mean	2392.40	1657.53	2274.70	1505.64	537.02	297.71
Standard deviation	763.27	662.94	720.49	618.48	326.61	194.05
Significance	P = 0.015		P = 0.018		P = 0.0008	

ure of the bone-screw interface was taken as the maximal pull-out force. For each traction load up to 2000 single measurements were performed and recorded by a Personal Computer.

Statistics

For comparison of implantation techniques performed on the same specimen, the Wilcoxon test for paired samples was used. For comparison of implantations performed on two different sacrum, the Student's *t*-test for unpaired samples was applied. First the data within each group were studied to establish the normal distribution. Data from two groups that did not originate from the same specimen were then investigated to establish the homogeneity of their variances. The significance level for each experiment was fixed at $\alpha = 0.05$. That means if the value of the probability of variation (*P*-value) was smaller than 5% ($P < \alpha$) the difference between the implantation techniques that were to be compared was considered significant.

Results

Convergent mono- and bicortical implantation techniques: comparison of axial pull-out forces

6-mm screws in the body of S1

Table 3 shows a clear superiority of the bicortical implantation technique using 6-mm screws. The results are highly significant ($P = 0.015$ by the Wilcoxon test).

7-mm screws in the body of S1

In Table 3 the results of the same experiment performed with 7-mm screws are also shown. These results are also highly significant ($P = 0.018$ by the Wilcoxon-test).

6-mm screws in the body of S2

The results of inserting a 6-mm screw into the body of S2 are to be found in Table 3. The statistical significance is very high ($P = 0.0008$ by the Wilcoxon test).

Figure 7 shows the maximum pull-out forces measured during all six previously described procedures regarding the mono- and bicortical implantation techniques. Both in

Fig. 7 Comparison of the mean pull-out force of the mono- versus bicortical technique in three different insertion techniques

S1 and S2 the bicortical implantation technique is superior to the monocortical method regardless of whether the screw diameter is 6 or 7 mm.

The pull-out strength of screws inserted into S1 was also noted to exceed that achieved in S2.

Screw diameter

Table 4 compares the axial pull-out forces measured for screws of different outer diameter. Figure 8 summarizes the results. The 7-mm screw does not achieve greater stability than the 6-mm screw.

Figure 9 summarizes all results as follows:

1. The body of S1 provides the most solid bone-screw interface for a bone screw; in the ala sacralis and the body of S2 markedly lower pull-out forces are reached.
2. The bicortical implantation technique is superior to the monocortical method.
3. The use of a 7-mm screw does not result in higher stability than using a 6-mm screw.

Discussion

Kraemer et al. [7] determined a maximal pull-out force of 925 N for a 7-mm screw with a continuous thread in pel-

Table 4 Effect of screw diameter (6 mm vs 7 mm) maximal pull-out force (in Newtons) for three different insertion techniques

	Convergent bicortical in S1		Convergent monocortical in S1		Divergent monocortical in the ala sacralis	
	6 mm (n = 9)	7 mm (n = 7)	6 mm (n = 9)	7 mm (n = 7)	6 mm (n = 14)	7 mm (n = 13)
Maximum	3388.2	3133.4	2455.2	2332.2	1011.5	769
Minimum	1267.7	1178.2	370.7	617	175	181.4
Mean	2392.40	2274.70	1657.53	1505.64	495.47	449.79
Standard deviation	763.27	720.49	662.94	618.48	244.55	184.59
Significance	P = 0.995		P = 0.726		P = 0.7897

Fig. 8 Comparison of the mean pull-out force of 6-mm- versus 7-mm-diameter screws in three different insertion techniques

Fig. 9 Comparison of all implantation techniques

vis specimens of people who had died at an average age of 76. The screw insertion was performed in a lateral to medial direction through the sacroiliac joint.

Smith et al. [15] determined the following data by testing 25 sacrum of an average age of 74 using mono- and bicortical techniques. In the body of vertebra S1, monocortical 590 N, bicortical 620 N; in the ala sacralis, monocortical 420 N, bicortical 430 N. However, the pull-outs were performed at a right angle to the screw axis.

Zindrick et al. [24] used lumbosacral spines of an average age of 74.5 years for their investigations. In the

sacrum they used 6.5-mm screws with a continuous thread. In all cases the ventral cortex was perforated. The highest axial pull-out forces were reached with a divergent screw location in the ala sacralis at the S1 level (1007 N). A pull-out force of 870 N was measured in the S1 pedicle, 688 N with a sagittal screw location in the ala sacralis at the S1 level, and 185 N in the S2 pedicle.

De Peretti et al. [13] used sacrum specimens from 20 healthy patients who had died at the average age of 32 years. They implanted a Cotrel-Dubousset screw in three different locations: (1) in the pedicle of S1 20° medioventrally, (2) in the pedicle of S1 directly sagittally and (3) in the ala sacralis at the S1 level approximately 30°–45° divergent. The ventral cortex was perforated in none of the cases. The pull-out forces in these three screw positions measured 700 N, 500 N, and 400 N respectively. By taking bone density measurements of the individual structures of the sacrum they found that the density was by far the lowest in the ala sacralis. The histological investigation of this region mainly revealed yellow fat-marrow surrounded by some trabecular spongiosa. This finding is especially interesting because de Peretti used specimens from young healthy patients.

A maximal pull-out force of 1520 N in the sacrum without perforation of the opposite cortex was found by von Strempel et al. [17, 18] in a study of 15 non-osteoporotic spines of healthy individuals who had died at an average age of 37.1 years.

Carlson et al. [5] examined 27 human sacrum with an average age of 76.7 years. They compared the pull-out strength of a 30° anteromedial screw position in the body of S1 to an approximately 40° anterolateral screw location in the ala sacralis, also at the S1 level. The ventral cortex had not been perforated. The pull-out tests were performed diagonally to the screw axis and gave a maximal strength of 580 N for the anteromedial location, and 77% of this value for the anterolateral screw position. Wittenberg et al. [21] determined an axial pull-out force of 337 N for the monocortical implantation technique in S1 after examination of five sacrum of an average of 78 years.

Studies of the stability of bone screws in the sacrum vary greatly not only in the values determined for maximal pull-out forces but also in the experimental conditions. Except for two investigators [13, 17, 18], all speci-

mens originated from very old individuals – an age group not representative of patients who undergo lumbosacral fusion. The experimental arrangements vary in a number of ways. Some use an axial, others a right-angled, pull-out direction. Both partially monocortical and bicortical implantations are undertaken. Among the screws that have been used, different outside and inside diameters and different kinds of threads and leads can be seen.

In our study the mean age of the specimens was 51 years and the mean trabecular bone mineral density was 118.2 mg Ca-HA/ml, which is typical for an age of 40–49 years in men [3].

Consequently both lateral (in the ala sacralis) and medial (in the S1 pedicle) screw positions are favored. After the study of the literature two results remain valid:

1. A bicortical implantation technique is better than a monocortical method
2. Bone density influences the stability of the screws

The alternative of screw insertion into the os ilium for the caudal fixation of rods, which was recommended by Baldwin and Benzel [2], raises the question of a possible irritation of the sacro-iliac joint and does not seem to be favorable for this reason.

The highly significant superiority of the bicortical screw position in the body of S1 described in this study raises the question of whether the technique is safe or not. Mircovic et al. [9] determined a so-called medial and lateral ventral safety zone after the study of 22 human pelvis specimens. The lateral safety zone is in an area located laterally of the plexus lumbosacralis and the internal iliac vein and artery, so that the screw tips can perforate the ventral cortex without danger during lateral implantation. This zone is very small compared to the medial ventral safety zone. The medial safety zone includes the ventral

circumflex of the S1 and S2 vertebral bodies up to the direct ventromedian course of the median sacral artery.

After investigation of five pelvis specimens, Licht et al. [8] defined an intermediate safety zone, which lies in the area of the ventral vertebral bodies of S1 and S2. Directly sagittal and anterolateral drill directions are considered risky.

Xu et al. [22] define two dorsal safety zones for screw insertion into S1, and recommend a drill direction originating more lateral from the S1 facet and converging at approximately 40°.

Different loads of the sacral screws in vivo, for instance in long instrumentations or in the presence of defects of the anterior column, were not investigated and cannot be described with the results of the presented study. More biomechanical research is necessary.

The advantage of the investigation of axial pull-out forces is the exactly defined direction of the screw load. In our opinion the results of these measurements allow a good judgement of the primary stability of the screw-bone interface.

Conclusions

On the basis of the study of 16 sacrum of individuals who had died without prior disease at a mean age of 51 years, different implantation techniques were investigated to establish the maximal axial pull-out forces. The bicortical screwing technique in the S1 pedicle turned out to be the most stable method (2392.40 N). The use of a 7-mm screw did not give significantly better results than a 6-mm screw. The alternative insertion points, in the pedicle of S2 and in the ala sacralis, showed clearly lower pull-out forces (537.02 N and 495.47 N respectively).

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