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Three-dimensional stabilization provided by the external spinal fixator compared to two internal fixation devices: a biomechanical in vitro flexibility study

Received: 17 July 2002
Revised: 9 November 2002
Accepted: 16 November 2002
Published online: 1 March 2003
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Abstract We performed an in vitro study to investigate the stabilization (i.e. motion reduction) provided by the external spinal fixator (ESF), and to compare the three configurations of the ESF with two internal fixation techniques. Six human cadaveric lumbar spine specimens (L3–S1) were subjected to multidirectional flexibility testing in six configurations: (1) intact, (2) ESF in neutral, (3) ESF in distraction, (4) ESF in compression, (5) translaminar facet screw fixation, and (6) internal transpedicular fixation. Both the ESF and the internal fixation systems stabilized the specimens from L4 to S1. In each testing configuration, pure bending moments of flexion-extension, bilateral axial rotation, and bilateral lateral bending were applied to the uppermost vertebra stepwise to a maximum of 10 Nm. The rigid body motion between the vertebrae was measured using an optoelectronic camera system, and custom software was used to calculate the intervertebral rotations. For each applied motion in all testing configura-

tions, the total range of motion (ROM) of L4–S1 is reported. All three ESF configurations stabilized the spine significantly when compared to the intact specimen. The ESF in compression provided significantly more stabilization in flexion-extension than the two other ESF configurations, but no other significant differences were found between the three ESF modes. In flexion-extension the ESF stabilized the spine significantly when compared with the two internal fixation devices. Only in bilateral lateral bending was the ESF inferior to internal transpedicular fixation in providing stabilization. The results of the present study suggest that the ESF provides a high degree of stabilization for preoperative assessment of selected low back pain patients. Whether other non-mechanical factors affect the pain relief experienced by the patients remains unknown.

Keywords Biomechanics · Lumbar spine · Low back pain · External spinal fixation · Internal spinal fixation

Introduction

Stabilization of the thoracolumbar spine in case of fractures or infections with an external spinal fixator (ESF) was introduced by Magerl [11]. Olerud et al. first suggested stabilization of the suspected symptomatic levels with the ESF in preoperative assessment of possible lum-

bar fusion candidates [12]. Since then, several clinical reports have stressed the value of the ESF test in evaluation of chronic low back pain (LBP) patients [3, 5, 16, 18], while others have adopted a more cautious attitude [8], and yet others have considered its use as unjustifiable because of low predictive value and high potential for serious complications [2, 6]. Undoubtedly, some chronic LBP patients do experience pain relief during the ESF test. The

basis of this pain relief is still unknown, but additional mechanisms other than stabilization of the suspected painful segments have been suggested [6, 13].

To date, only a few studies have addressed the biomechanical basis of the preoperative ESF test. In a thoracolumbar fracture model, the stabilizing effect of the ESF in flexion loading was superior to that of a Harrington distraction rod system [17]. Stalder et al. found the ESF to provide torsional and transversal stabilization to the functional spinal unit (FSU) [20]. With roentgen stereophotogrammetric analysis (RSA), Axelsson et al. confirmed the stabilizing potential of the ESF in anteroposterior translations in vivo [1]. However, despite the stabilization provided under bending moments, the ESF still allows substantial axial translation anteriorly under compressive loads [1, 10, 20]. Specifically, the biomechanical effectiveness of the ESF under axial compressive loading was strongly dependent upon the manner of its application, i.e. whether it was in a neutral, distracted, or compressed posture [10]. To our knowledge, this feature of the ESF has not been addressed previously in multidirectional flexibility testing. Nor has the biomechanical behavior of the ESF been compared to more standard posterior fixation techniques.

Therefore, the objectives of the present study were to investigate whether:

1. The ESF stabilizes the lumbar spine under three-dimensional bending moments with respect to the intact condition
2. The stabilization provided by the ESF differs between the different fixator configurations (i.e. neutral position, compression and distraction)
3. The stabilization provided by the ESF is comparable to that provided by two commonly used posterior internal fixation devices, namely internal transpedicular fixation and translaminar facet screw fixation

Materials and methods

Six human cadaveric spine specimens from L3 to S1 were used in this study. Their ages ranged from 31 to 55 years, and they exhibited mild to moderate degeneration macroscopically and radiographically. Before storage at -20°C , all non-ligamentous soft tissue was removed from the spine specimens. For the flexibility testing, the specimens were thawed, and the L3 vertebra and the sacrum were mounted in polymethylmethacrylate (PMMA) blocks such that the L4-L5 disc space was horizontal. Care was taken to keep the specimens moist throughout the preparation and testing phases.

A custom-made apparatus that has been used previously in several experiments [9, 14] allowed the application of known loads to the spine in an unconstrained manner (see Fig. 1). Pure moments of flexion-extension, bilateral lateral bending and bilateral axial rotation were applied to the uppermost vertebra in steps of 2.5 Nm to a maximum of 10 Nm. Before measurements, the specimen was allowed to creep for 30 s at each load step.

The relative motions between the vertebrae were measured using a precision optoelectronic camera system (Optotrak 3020, Northern Digital, Waterloo, Canada). For this purpose, each verte-

Fig. 1 The custom-made apparatus for multidirectional flexibility testing. Marker carriers with light-emitting diodes (LEDs) were attached to the vertebrae. Pure moments (here lateral bending) were applied to the uppermost vertebra, and the relative motion between the vertebrae was measured with a precision optoelectronic camera system

bra was mounted with a marker carrier having at least three non-collinearly arranged infra-red light-emitting diodes (LEDs) (see Fig. 1). The optoelectronic camera measured the relative motion between these marker carriers with a minimum accuracy of 0.15 mm. Customized software was used to calculate the intervertebral rotations of each vertebra with respect to the others in terms of Euler angles. For each applied moment under all testing configurations the motion in the direction of the applied moment was analyzed, and the total range of motion (ROM, i.e. the total motion under the maximum moment of 10 Nm) at L4-S1 was calculated. The values of the neutral zone (NZ) were generally of small magnitude, and were therefore not analyzed further.

All the specimens were first tested in an intact condition, i.e. with no additional instrumentation. The Magerl ESF (Stratec Medical, Oberdorf, Switzerland) was then mounted such that the Schanz screws of the fixator (6 mm in diameter) were inserted at levels L4 and S1 and connected with the two horizontal bars and three longitudinal threaded rods of the external frame. The specimens were tested with the fixator in neutral position, compression and distraction. Distraction and compression were defined by the way in which the frame was manipulated along the longitudinal rods, and was on average 12 mm. In one specimen the construction

Table 1 The median and mean ranges of motion (ROM) at L4-S1 with standard deviations (SD) in all directions for all the testing configurations, i.e. intact spine(intact), external spinal fixator in neutral (ESF_{neutral}), in distraction (ESF_{distr}) and in compression (ESF_{compr}), trans-laminar facet screws (TLS) and internal transpedicular fixation (USS)

	Intact	ESF _{neutral}	ESF _{distr}	ESF _{compr}	TLS	USS
Flexion-Extension ROM (°)						
Median	21.44	1.71	2.58	0.86	3.49	1.43
Mean	23.02	1.78	2.47	0.85	3.44	1.31
SD	5.66	0.53	0.69	0.44	1.78	0.54
Axial rotation ROM (°)						
Median	2.71	0.36	0.34	0.71	1.02	0.78
Mean	2.47	0.44	0.37	0.63	0.96	0.63
SD	0.93	0.39	0.27	0.41	0.40	0.37
Lateral bending ROM (°)						
Median	14.9	2.71	2.20	1.91	1.7	0.47
Mean	16.17	2.33	2.64	1.95	1.56	0.50
SD	3.59	0.72	0.95	0.44	0.84	0.11

of the ESF limited the compression to 8 mm. After removal of the external fixator, 3.5-mm titanium AO cortical screws (Stratec Medical, Oberdorf, Switzerland) were inserted segmentally at the L4-L5 and L5-S1 levels as translaminar facet screws according to the technique introduced by Magerl [11] and later described by Grob and Humke [7], and the testing protocol was repeated. Finally, the specimen was stabilized with a Universal Spine System internal fixator (USS, Stratec Medical, Oberdorf, Switzerland) by inserting 6-mm titanium pedicle screws to levels L4 and S1. For maximum fixation strength the screws were inserted such that they penetrated the anterior cortex of the vertebral bodies. A 200-N compression was applied between the screws before tightening the nuts, and finally a cross-link was added to the construct.

In summary, the six testing configurations were: (1) intact specimen, (2) ESF (L4-S1) in a neutral position, (3) ESF in distraction, (4) ESF in compression, (5) translaminar facet screw fixation at levels L4-L5 and L5-S1, and (6) transpedicular internal fixation (USS) from L4 to S1.

Nonparametric statistical methods were used in this study due to the small sample size. For the comparisons, first a Friedman ANOVA (i.e. nonparametric repeated measures) across all groups for each motion direction was calculated to detect any possible differences between the three ESF configurations. Then paired comparisons between the groups using a Wilcoxon matched-pairs test were run to compare the three different fixation systems. Statistical significance level was taken to be $P < 0.05$.

Results

The median and mean ROMs with standard deviations are presented in Table 1 for the intact specimen, the different ESF configurations, and the two internal fixation techniques. All the ROMs reported here represent the motion of the L4-L5 and L5-S1 levels combined.

In all directions, the three ESF configurations stabilized the spine significantly when compared to the intact situation (see Fig. 2). In flexion-extension, the median ROMs with the three ESF configurations were 4–12% of the intact motion, a statistically significant difference ($P = 0.028$ for all fixator configurations). In bilateral axial rotation, all the ESF configurations stabilized the spine significantly ($P = 0.028$ for all configurations), the median ROMs being 13–26% of the intact motion. The median ROMs in bilateral lateral bending were 13–18% of the in-

Fig. 2 The stabilization provided by the different external spinal fixator (ESF) configurations as compared to the intact specimen in all directions. The boxes represent the median range of motion (ROM) (L4-S1) at the maximum load of 10 Nm, and the whiskers show the non-outlier maximums and minimums. The statistical significance levels are indicated

tact specimen. These differences were statistically significant for neutral fixation ($P = 0.043$) and for the ESF in distraction and compression ($P = 0.028$).

The three different ESF configurations are compared in Fig. 3. In flexion-extension, the ESF in compression provided the most stable situation, with median ROM 50% of the neutral ROM ($P = 0.028$), and 33% of the distraction ROM ($P = 0.028$). The largest motion in flexion-extension was demonstrated with the ESF in distraction, although the difference from the neutral fixation was not significant ($P = 0.075$). In axial rotation, no significant differences were noted between the different ESF configurations, when comparing neutral to distraction ($P = 0.60$) and compression to distraction ($P = 0.30$). Likewise, in bilateral lateral bending, no differences in the stabilization of the three ESF configurations were detected, although there was a trend for the ESF in compression to stabilize the spine more efficiently than the other two configurations ($P = 0.11$ with respect to neutral fixation, and $P = 0.12$ with respect to distraction).

Fig. 3 Comparison of the stabilization provided by the different ESF configurations. The boxes represent the median ROMs (L4-S1) at the maximum load of 10 Nm, and the whiskers show the non-outlier maximums and minimums. The statistical significance levels are indicated. The arrows signify the statistical comparisons between the ESF in neutral and compression in the different loading directions

Fig. 4 Comparison of the stabilization provided by the ESF in compression to that provided by transaminar facet screws (TLS) and internal transpedicular fixation (USS). The boxes represent the median ROMs (L4-S1) at the maximum load of 10 Nm, and the whiskers show the non-outlier maximums and minimums. The statistical significance levels are indicated. The arrows signify the statistical comparisons between the ESF in compression and internal transpedicular fixation (USS) in the different loading directions

For comparing the stabilization provided by the ESF and the two internal fixation techniques, the ESF in compression was used, as it seemed to provide the most stable situation. These comparisons are illustrated in Fig. 4. It was of interest that in flexion-extension the ESF in compression provided the most stable situation when compared with both transaminar facet screws and internal transpedicular fixation. When compared with transaminar facet screws, the stabilization provided by the ESF was statistically significantly different ($P=0.028$), whereas the difference between the ESF and transpedicular inter-

nal fixation was not significant ($P=0.12$). In axial rotation, no significant differences were noted in the stabilizing potential of the three fixation systems. The median total ROMs of this two-level construct were on average less than 1° in bilateral axial rotation. In lateral bending, internal transpedicular fixation provided significantly more stabilization than either the ESF ($P=0.028$) or transaminar screws ($P=0.046$). However, the median ROMs in bilateral lateral bending did not exceed 2° after external fixation or fixation with transaminar screws either. No significant differences in lateral bending were found between the stabilization provided by the ESF and transaminar facet screws ($P=0.25$). When comparing the two internal fixation techniques, transpedicular fixation provided significantly more stabilization than transaminar facet screws in flexion-extension and lateral bending, but not in axial rotation.

Discussion

The basis of the pain relief experienced by some patients during the ESF test is still largely unknown. However, the concept of external spinal fixation in the preoperative assessment of chronic LBP patients is based on stabilizing the spine segments that are suspected of causing the patient's symptoms. In a thoracolumbar fracture model, Schlpfer et al. verified that in flexion loading the ESF provided better stabilization than the Harrington distraction rod system [17]. Later, Stalder et al. found the ESF to provide significant stabilization in axial rotation under torsional loading [20]. The stabilizing potential of the ESF in vivo was studied by Axelsson et al. with RSA [1]. They examined the patients in recumbent and erect positions with the ESF, and showed that the fixator significantly reduced the sagittal intervertebral translations. On the other hand, in vitro studies have shown that under axial compressive loads the ESF still allows substantial axial translation [10, 20], and does not reduce the loads acting on the disc [4]. Edwards et al. concluded that the ESF relieves pain by reducing flexion and inhibiting the bulging of the disc [4], but other factors than purely mechanical ones have also been suggested [6, 13].

The purpose of the present study was threefold: first, to define the stabilizing potential of the three possible ESF configurations (i.e. neutral position, distraction and compression) as compared to the intact spine; second, to compare the three different ESF configurations; and third, to compare the stabilization provided by the ESF with that of two commonly used internal fixation techniques. To the knowledge of the authors, this is the first study addressing the biomechanics of the ESF, and comparing the different ESF configurations under multidirectional flexibility testing.

The results of the present study showed that all three ESF configurations significantly stabilized the spine in

the two-level model in all directions when compared to the intact spine. No significant changes could be demonstrated between the stabilizing potential of the three different ESF configurations, except in flexion-extension, where the ESF in compression provided significantly more stabilization than either the neutral fixation or fixation in distraction. In flexion-extension, the ESF in distraction provided the least stabilization, probably because of distraction of the facet joints and the degenerated "empty" disc. However, the stabilization provided by the distracted ESF was still significantly different from the intact spine. In bilateral axial rotation and lateral bending, no significant differences between the three ESF configurations could be detected. In clinical practice, pain relief during ESF has been reported with the fixator in neutral position, compression, and distraction [8, 16, 18]. Our results suggest that neutral fixation is mechanically adequate in evaluation of LBP patients, and adjustments to distraction or compression may not give any additional mechanical effect, confirming the statement by Stalder et al. [20].

The stabilization provided by the ESF was in general equal to the stabilization achieved by translaminar facet screw fixation and internal transpedicular fixation. Interestingly, a trend was observed for the ESF to reduce motion in flexion-extension more efficiently than internal transpedicular fixation, even though this difference was not significant. One might have expected that the long moment-arm of the ESF would result in reduced stabilization compared to the internal transpedicular fixation device, which lies closer to the posterior elements. In lateral bending, internal transpedicular fixation stabilized the spine significantly better than the two other techniques, but again, the stabilization provided by the ESF was significant when compared to the intact specimen.

For the flexibility testing, a two-level construct from L4-S1 was selected, as several reports have concluded

this to be the situation most frequently encountered clinically [8, 12, 19]. The specimens were graded as mildly to moderately degenerated, but no specific injuries to the posterior stabilizing structures or the discs were created before the testing. It is possible that, for instance, deficient posterior elements might have affected the results of the present study. Likewise, as in most in vitro studies, the effect of muscles on the stability of the FSUs is difficult to evaluate. In an in vitro study, Quint et al. demonstrated that simulated muscle forces caused a decrease in the ROM during axial rotation and lateral bending in an intact specimen as well as after laminectomy, but a slight increase in the ROM followed flexion loading [15]. However, no significant changes in the ROMs were observed when muscle forces were applied to a specimen after rigid stabilization. Thus, the effect of muscle forces in our study would probably be minimal in the ESF and USS testing configurations, whereas the effect of muscle forces on the specimens stabilized by translaminar facet screws might be more pronounced.

Conclusions

All the ESF configurations, i.e. neutral fixation, compression and distraction, provided significant stabilization when compared to the intact specimen, and only in flexion-extension was there a significant difference between the different ESF configurations. The stabilization provided by the ESF compared favorably with the two internal fixation techniques. Thus, the results of the present study suggest that the mechanical basis for the ESF test in preoperative assessment of chronic LBP patients is sound. Whether or not additional non-mechanical factors influence the pain relief experienced by some chronic LBP patients during the ESF test should be the focus of future studies.

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