A Comparative Biomechanical Evaluation of Various Instrumentation Techniques at Lumbopelvic Junction

Çeşitli Enstrümentasyon Tekniklerinin Lumbopelvik Bileşkede Karşılaştırmalı Biyomekanik Değerlendirmesi

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Geliş Tarihi/*Received:* 14.01.2013
Kabul Tarihi/*Accepted:* 23.04.2013

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ABSTRACT Objective: A well-supported fixation is generally imperative to stabilize spinopelvic junction in case of sacrectomy or neurologic diseases that deteriorate the spinopelvic balance. A comparative biomechanical study was designed to evaluate various fixation techniques for long spinopelvic stabilization. **Material and Methods:** A total of 40 in vitro calf spine models were used. Five groups (one control and 4 study groups), each having 8 samples, were created. In the study groups, lumbosacral junctions were stabilized either with L3-S1 bilateral pedicle screws connected to rods (group 1), with L3-S1-iliac screws (group 2), with L3-S1-dual iliac screws (group 3) or with a combination of rods in which the initial L3-S1 fixation was connected to the transiliac bar system with oblique connectors (group 4). The compression behavior of each model and control group were tested under axial loading by using a universal testing system. Statistical analysis was done to compare yield load, displacement at yield and stiffness within groups and to compare study groups with the control group. **Results:** All groups were significantly stiffer than the control group. Group 4 exhibited the highest (median: 11253 N) yield load (min:11247-max:11259) among the groups. The highest load displacement at yield point (median: 11.4 mm) (11.2-11.6 mm) amongst all tested systems was reached at group 2 ($p<0.001$). The statistical analysis, however, showed a significant difference between groups 4, 2 and 3 in terms of yield load, displacement at yield and stiffness ($p<0.001$). Although group 4 had the highest yield load, the stiffness of group 3 was slightly higher than group 4 ($p<0.001$). However, there was no statistically significant difference between group 2 and the control group in terms of stiffness ($p=0.083$). **Conclusion:** The four-rod fixation technique with obtaining additional stability from ilium provides a better yield strength when compared to other techniques. This system not only ensures a more stable construct, but also can lower the need for an anterior support.

Key Words: Spine; biomechanics

ÖZET Amaç: Spinopelvik dengeyi bozan sakrektomi ya da nörolojik hastalık durumlarında, spinopelvik bileşkenin stabilizasyonu için genellikle iyi desteklenmiş bir tespite ihtiyaç vardır. Spinopelvik stabilizasyon için çeşitli fiksasyon tekniklerini değerlendirmek üzere karşılaştırmalı biyomekanik çalışma tasarlandı. **Gereç ve Yöntemler:** Toplam 40 dana omurgası kullanıldı. Her birinde 8 örnek olacak şekilde 5 grup (bir kontrol ve 4 çalışma grubu) oluşturuldu. Çalışma gruplarında, lumbosakral fiksasyon, ya L3-S1 bilateral pedikül vidalarının rodlara tutturulması (grup 1), ya L3-S1-iliyak kemiğe (grup 2), ya L3-S1-çift iliyak vida (grup 3) ya da ilk L3-S1 fiksasyonun rodlarla birlikte oblik konnektörlerle transiliyak bar sistemine iliştirilmesi (grup 4) ile sağlandı. Her bir modelin ve kontrol grubunun kompresif davranışı evrensel test sistemi kullanılarak test edildi. Çökme yükü, çökme sırasında deplasman miktarı ve sertlik gruplar içinde istatistiksel olarak karşılaştırıldı. **Bulgular:** Tüm gruplar belirgin olarak kontrol grubundan daha dayanıklıydı. Tüm gruplar içinde en yüksek akma dayanımını grup 4 (medyan: 11253 N) gösterdi (min:11247-maks:11259). En yüksek akma dayanımı noktasında en yüksek deplasmanı ise grup 2 (medyan: 11,4 mm) (11,2-11,6 mm) gösterdi ($p<0,001$). Ancak, akma dayanımı, çökme esnasında deplasman miktarı ve sertlik göz önüne alındığında, grup 4 ile grup 2 ve 3 arasında istatistiksel olarak belirgin fark vardı ($p<0,001$). Grup 4 en yüksek akma dayanımına sahip olsa da, grup 3'ün sertliği grup 4'ten daha fazlaydı ($p<0,001$). Sertlik değerlendirildiğinde ise grup 2 ile kontrol grubu arasında istatistiksel olarak anlamlı fark yoktu ($p=0,083$). **Sonuç:** Diğer tekniklerle karşılaştırıldığında, iliyumdan sağlanan ek stabilite ile 4 rodlu fiksasyon tekniği daha iyi akma dayanımı sağlamıştır. Bu sistem stabil bir fiksasyonunun yanı sıra, ek anterior destek ihtiyacını azaltabilir.

Anahtar Kelimeler: Omurga; biyomekanik

doi: 10.5336/medsci.2013-33901

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Turkiye Klinikleri J Med Sci 2013;33(4):1175-81

Failure of pelvic fixation is usually caused either by flexion angular loading with or without axial rotation, or by lateral bending especially when using a long lever arm consistent with a long T2-pelvis typical construct. A recent study on four different lumbopelvic fixation techniques has reported significant improvement in stiffness of system with use of S1 screws and iliac screw fixation when compared with using S1 and S2 screws during cyclic and ultimate load testing.[1] The authors suggested the use of S1 and iliac screws and placement of iliac bolt connector proximal to S1 screw. Despite these improvements, controversy still exists and continues to be a problem regarding lumbosacral fusions.[2-5]

Because of complexity of the biomechanical forces acting on the lumbosacral junction, various studies have reported high complication rates such as pseudoarthrosis, implant loosening, screw breakage or loss of fixation.[6,7] In order to accomplish a better fixation, multiple fixation techniques have been reported.[1,8-14]

In this study, we examined the differences in load and stiffness of different four-rod lumbopelvic fixation techniques, namely lumbosacral fixation, iliolumbosacral fixations with either single bilateral iliac or a pair of bilateral iliac screws. We hypothesize that four-rod system which involves iliolumbar and lumbosacral parts will have a greater stiffness in axial compression compared to conventional techniques. The main aim of this study was to assess whether including a transiliac bar into the lumbosacral fixation by a newly designed multiplane pipe type connector has an additive effect in obtaining a better fixation.

MATERIAL AND METHODS

Forty skeletally mature, fresh-frozen, male calf spines with intact lumbopelvic junctions (obtained from the Turkish Meat & Fish Association) were used to determine load displacement (mm), stiffness (N/mm) and yield load (N) for various fixation techniques in spinopelvic fixation. In addition, the surrounding posterior paravertebral tissues were remained intact during test preparation. The spines were stored in a freezer at -20°C before spinopelvic fixation. During biomechanical testing, the specimens were kept moist with 0.9% NaCl soaked gauze. A prospective radiographic analysis of the specimens was performed before biomechanical testing to exclude any anatomical abnormalities or osteopenia.

SPECIMEN PREPARATION

Before surgical procedures and biomechanical stability measurements, the frozen spines were thawed at room temperature for 48 hours. The posterior part of superior endplate of L3 vertebra corpus was beveled with an oscillating bone saw to ensure that the specimen could be properly mounted to the testing device. The distal end of the specimen was inferiorly secured to the system with anterior and posterior transverse bars. To ensure a stable fixation and to locate the axis of rotation center right at the middle-column of the S1, bilateral 6.0 mm threaded rods were fixed into opposing sides of the anterior inferior iliac spines, parallel with the lower table of the testing device.

Five groups of samples (8 specimens for each group) were prepared for biomechanical tests. Four groups with different fixation techniques and a control group was tested. For each group, diameter and size of the screws and rods were exactly the same for each level. Before biomechanical testing, specimens were randomly assigned into each group according to following lumbopelvic fixation techniques:

Control group: The control group was tested without any fixation technique.

Group 1: Lumbosacral fixation was consisted of fixation from L3 to S1 with bilateral pedicle screws (6.5 mm in diameter and 45 mm in length). Two 6.0 mm- diameter rods were connected to the screws, and no transverse connector was used.

Group 2: Modified Galveston technique with fixation of L3 to S1 with bilateral pedicle screws with addition of iliac screw one for each side.

Group 3: In addition to Modified Galveston, bilateral dual iliac screws connected to each rod by short secondary rods were used for this group.

Group 4: A novel technique consisting of four rod- system involving two separate instrumentations was used. Two bilateral rods were assembled to the transiliac bar by a newly designed multiplane pipe type connector (Tasarımmed, Istanbul, Turkey), and this system was connected to the rods that extended from L3 to S1 with oblique connectors (Figure 1).

BIOMECHANICAL TESTING

The prepared spines were mounted on the Instron (Instron Corporation, 825 University Avenue, Norwood, MA 02062-2643 USA) testing device. The superior endplate of L3 was mounted as described before, to provide axial compression by the Instron testing frame through the lumbar spine and pelvis. Calf spines were fixed to a customized apparatus to enable the flexor force vector to be applied in direct alignment with the instant rotation center. The prepared spines were mounted to the Instron testing frame as shown in Figure 2. Axial compression was applied from instantaneous motion center of L3 bone with a rotation free joint for flexion. Displacement versus load values were recorded during the tests.

FIGURE 1: A detailed view of spinopelvic construct with use of multiplane connector and oblique connectors.
(See color figure at http://tipbilimleri.turkiyeklinikleri.com/)

FIGURE 2: Biomechanical testing by Instron device connected to a data taker and computer.
(See color figure at http://tipbilimleri.turkiyeklinikleri.com/)

Loading data were recorded by Bluehill software (Instron Inc.) which recorded ten values for a second. The loading procedure ensured the same starting point for all specimens and thus had the ability to make reliable comparison between different fixation techniques. For each technique, load displacement (mm), load stiffness (N/mm), yield load (N) and ultimate failure load (N) were recorded. Ultimate load is defined as the maximum endured load during testing. Yield load is defined as the load value corresponding to the intersection of load-displacement curve with 0.02% off-set line drawn parallel to linear region of the curve. Due to prior reports of a decreased tissue stiffness and strength with desiccation, tissues were frequently hydrated with a saline filled spray bottle during all stages of specimen preparation and testing.

All data were recorded as median (min-max). Statistical analysis was performed by using SPSS version 15.0 software (SPSS, Inc., Chicago, IL) and included Kruskal Wallis analysis. When the p value from Kruskal Wallis test statistics was statistically significant, Bonferroni Adjusted Mann Whitney U test was used to know which group differed from the others. $p<0.05$ was considered as statistically significant. However, Bonferroni Correction was applied for Type I error for all multiple comparisons.

RESULTS

All specimens failed at the most distal level of fixation. In groups 1 and 4, failure was seen at the S1 pedicle screw-bone interface and in groups 2 and 3, this was at iliac screw-bone interface. All groups were significantly stiffer than the control group. Group 4 exhibited the highest (median: 11253 N) yield load (min:11247-max:11259) among the groups. The highest load displacement at yield point (median: 11.4 mm) (11.2-11.6 mm) was reached at group 2 amongst all tested systems ($p<0.001$). Axial compression test results for the control group and groups 1, 2, 3 and 4 are given in Table 1.

Measurement of yield load showed statistically significant differences between instrumented groups and the control group ($p<0.001$). The differences of median yield load between group 4 and control group, group 1, 2 and 3 were statistically significant ($p<0.001$). Displacement at yield point was significantly higher in group 2 ($p<0.001$). The lowest difference was obtained between groups 1 and 2 ($p=0.007$).

The most stiff system was group 3 (median: 1109.5 N/mm) (1086-1133 N/mm) ($p<0.001$). The statistical analysis, however, showed a significant difference between group 4 and 2 and 3 in terms of yield load, displacement at yield and stiffness ($p<0.001$). Although group 4 had the highest yield load, the stiffness of group 3 was slightly higher than group 4 ($p<0.001$). However, there was no statistically significant difference between group 2 and the control group in terms of stiffness ($p=0.083$). Use of an iliac screw (in Group 2) decreased the yield point of system up to 20% when compared to Group 1. Similarly, Group 3 type fixation also decreased the yield point of system to some extent. Parallel to these findings, stiffness of Group 1 was 15% higher than Group 2. Stiffness and yield strength of Group 4 type fixation was 1.7 and 3.5 fold greater than the control group, respectively.

TABLE 1: Comparison of axial compression measurements among the groups.

	YL (N)	DY (mm)	S (N/mm)
Control (n:8)	3231 (3205-3269)	5.1 (5.0-5.3)	633 (610-654)
Group 1 (n:8)	9240.5 (9235-9254)	11.1 (11.0-11.4)	829.5 (810-840)
Group 2 (n:8)	7299 (7285-7325)	11.4 (11.2-11.6)	640.5 (630-652)
Group 3 (n:8)	5104 (5089-5121)	4.6 (4.5-4.7)	1109.5 (1086-1133)
Group 4 (n:8)	11253.5 (11247-11259)	10.9 (10.6-10.9)	1033 (1032-1062)
p-value	<0.001	<0.001	<0.001
Multiple Comparisons†			
Control vs Group 1	p<0.001	p<0.001	p<0.001
Control vs Group 2	p<0.001	p<0.001	p=0.083
Control vs Group 3	p<0.001	p<0.001	p<0.001
Control vs Group 4	p<0.001	p<0.001	p<0.001
Group 1 vs Group 2	p<0.001	p=0.007	p<0.001
Group 1 vs Group 3	p<0.001	p<0.001	p<0.001
Group 1 vs Group 4	p<0.001	p<0.001	p<0.001
Group 2 vs Group 3	p<0.001	p<0.001	p<0.001
Group 2 vs Group 4	p<0.001	p<0.001	p<0.001
Group 3 vs Group 4	p<0.001	p<0.001	p<0.001

YL: Yield Load; DY: Displacement at Yield; S: Stiffness. All data are expressed as median (min-max).

†: According to the Bonferroni Correction $p<0.005$ ($\alpha/k=0.05/10$) was considered statistically significant.

DISCUSSION

The results of this study show that the new technique does appear to become an alternative to conventional lumbosacral fixation techniques. This technique appears to be easier and requires less exposure and stripping. Yet the instrumentation proposed seems to be quite bulky and does raise the question of whether this would decrease room for fusion, implanting a transiliac bar, connection of the bar with pipe type connector. In addition, connection of this system onto the lumbar rods with oblique connectors can prevent the most disfavored situations such as hardware prominence, implant loosening and the need for a wide exposure. To our knowledge, this is the first study which biomechanically evaluates and compares biomechanical properties of various fixation methods, and the new fixation technique which receive additional buttress effect of iliac wings into the lumbosacral instrumentation.

The most common indications for lumbosacral fusions are spondylolisthesis, flat back syndrome, pelvic obliquity and pseudoarthrosis. However, due to the osteopenic bone in the sacrum, the reported failure rate of sacropelvic fixation with either only S1 or with the addition of S2 pedicle screws has been shown to be as high as 44%.[15,16] After introducing Galveston technique and its modifications, ilium was used to improve the stiffness of the system. Unlike sacral screws, iliac rods or screws increase the caudad purchase and pull-out strength of the screws.[17]

Several fixation options were revolutionized for stabilization of lumbosacral junction due to the complexity of the biomechanical forces. These techniques aim to decrease shear forces across the lumbosacral junction. Kelly et al. introduced four-rod technique either with or without cross-links, and they compared their system with traditional cross-linked two rod techniques.[1] Additionally, the study by Kelly et al., which describes theory and technical considerations of four-rod techniques, and also study by Sheen et al. have recommended this technique for complex spinopelvic reconstructions owing to the increased proximal and distal fixation.[1,13]

Although high fusion rates can be obtained, there are some disadvantages related to these systems. Contouring and to placing a rod into ilium is very difficult; after placement, hollows around the rods and screws (windshield wiper sign) were reported because of occurrence of micromotions.[1,18,19] Furthermore, hardware prominence, higher infection rate due to need of extended exposure, iliac screw backout and rarely acetabular joint violation were also reported.[19,20] We think that the proposed technique does not possess such disadvantages. In this study, similar to modified Galveston techniques, we found that the new four-rod spinopelvic fixation system can withstand higher initial failure and ultimate failure loads compared to traditional fixation techniques. In fact, this uniformity can help to eliminate the need for anterior support in obtaining an efficient circumferential fusion mass.

This system resembles the Kostuik transiliac bar technique and differs from it by not crossing the sacroiliac joint.[7] Its technical ease makes its implantation more practical because properly designed rod with a multiplane pipe type connector at the distal end can be easily attached to the transiliac bar. Considering the technical difficulties involving connection problems of intrasacral rods or iliosacral screws and contraindication of use Kostuik transiliac bar technique without anterior column support, this new system can contribute some advantages into spinopelvic fixation.[21] This novel fixation technique relies on creating a stiff construction around the lumbopelvic junction. The technique uses both the posterior superior iliac spine which has a large area of spongious and cortical tissue for buttress effect and S1 screws to take the lumbosacral pivot point anteriorly.[19] As described before by McCord et al., stiffness can be obtained by taking the construction anterior to the lumbopelvic pivot point.[5] In addition, a hypothetical advantage of using transiliac bar is the reduction of the strain on the S1 screws which prevents implant loosening or breakage.[22]

We found only one comparative biomechanical study that used linked-four rod system in the related literature.[8] This previous study used a sacrectomy model in which pelvic fixation was achieved by iliac screws. The authors concluded that the linked-four rod (LFR) system had superior stiffness when compared with other traditional techniques. These investigators found similar values of a median displacement for their three different spine conditions. In flexion, higher decrease of spinopelvic flexibility (41%) was achieved by LFR system. Although similar conclusions can be drawn, our study differs in terms of biomechanical testing method and the test material. Our rationale for using calf spine was proximate properties of calf spine to human lumbopelvic junction. Buttermann et al. have shown similarities between human lumbar motion segment and runt cow lumbar motion segments in terms of transverse disc size, flexibility characteristic and intradiscal pressures at static positions.[13] The authors concluded that calf lumbar spine was suitable for in vivo biomechanical testing of spinal implants.

Our study has some limitations. It would be ideal to conduct the tests using young human cadaver specimens. However the cost, insufficient numbers, and the fact that available specimens from elderly cadavers did not have the same material qualities as young human cadaver specimens, limited the study. Moreover, the calf spine model has been previously described as an effective alternative for biomechanical testing. Therefore calf spine was used in place of human tissues.

The second limitation is that only axial loading was used to simulate flexion/extension motion. Although the flexor moment is the most important load in terms of pull-out strength, the spine and the lumbopelvic junction are exposed to various types of forces in daily activities. Only axial force is applied to the instantaneous rotation axis directed at the L4-L5 disc, and this represents the "worst-case scenario" though it may not be representative of an in vivo situation such as the case of an immediate postoperative patient who underwent a severe accident. Furthermore, conducting only static tests is the main limitation of this study. In order to understand the long term performance of fixation techniques, cyclic loading must also be studied. However, conducting cyclic loading tests requires controlled atmosphere and long term heat and humidity control. Otherwise, calf spine samples will rot and soft tissues will loose their properties. Therefore, cyclic loading tests have not been performed.

CONCLUSION

The four rod system including multiplane pipe type and oblique connectors that combine ilium and lumbosacral spine was able to withstand higher ultimate failure loads and was also stiffer than lumbosacral fixation techniques or the Galveston techniques with either bilateral iliac screw alone or a pair of bilateral iliac screws. Under axial loading, The four-rod technique provides better stability when compared to conventional fixation techniques. Combination of transiliac bar technique and sacral pedicle screws seem to increase allover strength of the construct by adding buttress effect and taking the lumbosacral pivot point more anteriorly. Connection of rods by multiplane and oblique connectors can help to decrease operation time and need for an expanded exposure and can prevent hardware prominence especially at thin patients. These findings may prove useful to the surgeon desiring an additional stability when considering long fusion segments involving lumbosacral junction in a difficult case or in a patient with a poorer bone stock.

Acknowledgement

We are grateful to Bunyamin Yavuz, M.D. who gave so generously of his time for the statistical analysis of the data.

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