A biomechanical comparison of three spondylolysis repair techniques in a calf spine model

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Summary

Summary of background data: Previous work has demonstrated the efficacy of lumbar pedicle screw hook rod (PSHR) techniques and the Buck screw in the stabilization of spondylolysis. The mechanical behavior of lower profile cervical implants used to create PSHR, hybrid cable plate constructs, and titanium miniplating has not previously been described.

Methods: Calf lumbar spines (L2-L6) were utilized for testing (n = 27). Intervertebral rotation was measured in the intact spines across the L4-5 segment before and after creation of bilateral pars interarticularis defects. Defects were then stabilized with one of three repair techniques, PSHR, miniplate, or cable plate (CP) constructs. (n = 9). A 5-Nm load was applied in flexion-extension, lateral bending and axial rotation. Fracture displacement was measured under flexion-extension and lateral bending modes.

Results: Osteotomy of the pars interarticularis increased intervertebral rotation from 4.6° to 9.2° (P < .05). The three techniques of repair reduced intervertebral rotation without statistical superiority of one method. In lateral bending the miniplate was most effective in reducing pars defect displacement (0.6 mm, P < 0.05). Although, the miniplate provided lower defect displacement in flexion-extension and axial rotation, these differences were not statistically significant.

Conclusions: Bilateral miniplate fixation demonstrates superiority in restoring stability in lateral bending as compared to pedicle screw hook rod techniques and cable plate constructs. In flexion-extension and axial rotation, it was as effective as a PSHR method. Consideration of anatomic plate designs warrants consideration.

Level of evidence: IV.

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Introduction

Spondyloysis is an acquired stress fracture of the pars interarticularis, which occurs in childhood or adolescence. When the lumbar spine is extended, pressure is transmitted from the superior vertebra’s inferior articular process to the inferior vertebra’s pars interarticularis [1,2]. Sports such as tennis, gymnastics, football, and swimming, require more lumbar hyperextension leading to a higher percentage spondyloysis in these populations [3–8].

For the child or young adult with disabling symptoms, which preclude participation in vigorous activity, or with significant pain with activities of daily living, surgical intervention may be warranted [9]. Surgical options for repair of the pars interarticularis parallel those used for repair of any pseudoarthrosis. Debridement of fibrocartilaginous debris from a typical defect results in the creation of a segmental bony defect, which must be filled. A structural autologous bone graft has been advocated to bridge the defect and to prevent iatrogenic shortening of the pars interarticularis during the application of compression across the non-union site [10].

Multiple methods of internal fixation have been described as a means of stabilization of the spondylolytic defect. One of the earliest techniques described is the Scott Technique, which consisted of a wire looped around the spinous process and lamina, stabilized to the transverse process [11]. This technique has largely been abandoned due to the difficulty of the technique and the development of better options. Bilateral screw fixation placed across the lamina and into the pedicle base (Buck’s technique) is inherently appealing given the capacity to provide compression across the defect [12]. The difficulty of achieving an appropriate screw trajectory combined with the risk of screw fatigue has prompted a search for more effective means of repair [13]. Use of a hook screw has been described with a laminar hook applied to the caudal end of the lamina and anchorage into the junction of the superior facet and lamina on the same side [14]. The use of bilateral pedicle screws attached to a V-shaped rod applying cranially oriented compression force to the spinous process has been described [15]. Finally, bilateral screw fixation attached to laminar hooks via longitudinal rods has been described combined with structural bone grafting of the debrided pseudoarthrotic defect [16]. This technique of repair has been shown in biomechanical studies to have equivalent mechanical performance in stabilization of the pars interarticularis defect when compared to the Buck technique [17].

The existence of a plethora of stabilization techniques provides an insight into the problems associated with pars defect repair. While the aforementioned methods provide varying of stability, all have some inherent drawbacks. In an attempt to improve upon the existing methods, we sought to investigate the utilization of smaller implants to lessen the likelihood of implant prominence. In addition, we propose that the technique of repair include a buttress effect using a plate applied dorsal to the lamina and pars to prevent dorsal migration of an applied structural bone graft.

Figure 1 Bilateral spondylolytic defects in L4 using an oscillating saw.

Materials and methods

Biomechanical Study

Twenty-seven fresh frozen calf lumbar spines (male Holstein species, aged 7–14 days, average weight 50 kg at harvest) were obtained and stripped of unnecessary muscle tissue while maintaining all ligaments and joint capsules. L2 and L6 were embedded in polymethylmethacrylate allowing motion at L2-3, L3-4, L4-5, and L5-6. Testing was performed on specimens before and after creation of bilateral spondylolytic defects in L4 using an oscillating saw (Fig. 1). Specimens were maintained in a subzero freezer and thawed overnight prior to testing. Each specimen was prepared and tested over a 2-week period. Subsequently, three repair techniques—pedicle-screw-hook-rod, arch plate, and cable plate constructs—were applied with nine spines per group (Figs. 2–4).

Biomechanical testing

L2 and L6 were attached to custom grips for attachment to the Instron. Loads were applied using an Instron 1122 Materials Testing Machine (Instron Corporation, Norwood, MA) with a spine-testing fixture described in previous publication from our laboratory [18]. Testing was performed in axial rotation, lateral bending, and flexion/extension using an applied load of 5 Nm with a 50-N compressive preload to simulate the effects of the in vivo muscular envelope. Specimens were subjected to two preconditioning load cycles with data collected from the third cycle used for analysis. Intervertebral rotation was measured across the L4-5 motion segment using a custom rotational transducer. The rotational transducer was rigidly fixed to the L4 and L5 vertebral bodies using K-wires and a mini vertebral halo ring (Fig. 5A & B). In addition, displacements across the defects on each side were measured by linear extensometers and were averaged. Data acquisition was continuous throughout each test at a sampling rate of 10 Hz and stored in a computer data file. Data analyzed included intervertebral
rotation at L4-5 under torsional load (axial rotation), displacement across the fixed defect in lateral bending, and flexion/extension.

Statistical methods

One-way analysis of variance (ANOVA) was used to test for any significant differences ($P < 0.05$ significant) between spine condition (intact, unstable, or repaired) and treatment groups (pedicle-screw-hook-rod, arch plate, or cable plate) in axial rotation, flexion/extension, and lateral bending. Post-hoc Fisher’s protected least squares difference (PLSD) tests were performed to detect pair-wise differences when appropriate. A pretest power analysis predicted that twenty-seven specimens were required to reach statistical significance.

Results

Specimens were generally of the same size and shape. Catastrophic failure did not occur in any of the motion segments or in any of the instruments all through the biomechanical testing. All needles holding the extensometers in the spinal elements were confirmed stable after each series of testing.

Intact spines refer to spines without the spondylolytic defects. Unstable spines refer to spines with bilateral spondylolytic defects but without fixation devices. Stabilized spines refer to spines with bilateral spondylolytic defects with fixation devices. The three fixation devices utilized in this study as mentioned above are the arch plate, cable plate, and pedicle-screw-hook-rod.

Results in axial rotation

Prior to osteotomy of the pars interarticularis, an average of $4.6^\circ$ of intervertebral rotation was measured across the L4-5 segment ($n = 27, SD = 1.6, SE = 0.31$). Bilateral osteotomy of the pars interarticularis increased the mean intervertebral rotation to $9.2^\circ$ ($n = 27, SD = 4.3, SE = 0.84$) When examined in aggregate, all three methods combined reduced intervertebral rotation to a mean of $6.5^\circ$ ($n = 27, SD = 3.2, SE = 0.84$) (Fig. 6). The difference between all means was statistically significant using Fisher’s exact test.

The titanium mini plate (arch plate) was most effective at reduction of intervertebral rotation with reduction of intervertebral rotation to $5.6^\circ$ ($n = 9, SD = 3.2, SE = 1.1$). The cable plate method reduced intervertebral rotation to $6.86^\circ$ ($n = 9, SD = 3.1, SE = 1.1$) and the pedicle screw-hook-rod method was least effective in the reduction of intervertebral rotation to normal values with a mean intervertebral rotation of...
Figure 5  A. Rotational transducer rigidly fixed to L4 and L5 vertebral bodies using K-wires and a mini vertebral halo ring. B. Schematic drawing of experimental setup: A) cemented potting superior lumbar segments; B) cemented potting inferior lumbar segments; C) L4 vertebral body; D) L5 vertebral body; E) K-wire affixed to L4; F) K-wire affixed to L5; G) halo ring affixed to L4 K-wire; H) halo ring affixed to L5 K-wire; I) transducer affixing two halo rings with connection to Instron device.

Figure 6  Osteotomy of the pars interarticularis doubled the amount of intervertebral rotation ($P < 0.05$). Stabilization of the pars interarticularis produced a significant reduction in the amount of intervertebral axial rotation ($P < 0.05$). 7.2° ($n = 9$, $SD = 3.3$, $SE = 1.1$). While the miniplate method showed the greatest trend towards reduction of intervertebral rotation, the differences between the mean values was not statistically significant. The mean values seen with each stabilization method used are depicted in Fig. 7 below.

Flexion-extension results

All fixation methods resulted in some degree of displacement across the stabilized pars interarticularis defect when subjected to flexion-extension rotational torque. As we recorded data from the left and right pars interarticularis defects in flexion-extension and lateral bending, nine sets of paired data or 18 data points were available per construct tested. The titanium miniplate (arch plate) was most effective in reducing spondylolysis gap displacement with a mean displacement of 1.1 mm ($n = 18$, $SD = 0.93$, $SE = 0.22$). The cable plate construct and PSHR methods showed greater of gap displacement with the cable plate technique allowing 1.5 mm of gap displacement ($n = 18$, $SD = 1.6$, $SE = 0.38$) and the PSHR method allowing 1.4 mm gap displacement ($n = 18$, $SD = 0.92$, $SE = 0.22$). The differences between the mean values recorded did not reach statistical significance. The mean values noted are depicted in Fig. 8.

Lateral bending results

When subjected to rotational torque in lateral bending the arch plate was significantly more effective in reducing pars defect displacement than the cable plate or PSHR methods. The arch plate demonstrated a mean gap displacement of 0.59 mm ($n = 18$, $SD = 0.52$, $SE = 0.12$), while the cable plate method allowed a mean of 1.3 mm gap displacement ($n = 18$, $SD = 0.96$, $SE = 0.23$) and the PSHR method allowed 1.2 mm gap displacement. The mean difference between the arch plate and cable plate was statistically significant ($P < 0.05$) while the difference between the arch plate and
There were no significant differences in fracture gap displacement between the three constructs tested in flexion-extension.

In lateral bending, the titanium miniplate was significantly better in reducing gap displacement when compared to the PSHR and cable plate ($P < 0.05$). PSHR approached statistical significance ($P = 0.052$). Results in lateral bending are depicted graphically in Fig. 9.

Discussion

Axial rotation testing

Using our testing methodology, an average of $4.6^\circ$ of intervertebral rotation was recorded at the L4-5 segment in intact spine specimens ($n=27$). Deguchi and Zdeblick [17] in contrast reported $3.25^\circ$ mean intervertebral rotation in their intact bovine spine group. These values compare favorably to human and calf spine biomechanical data published by Riley et al. who reported a mean axial rotation of $2.1^\circ$ in a bovine model and $4.7^\circ$ in a human cadaveric model [19]. The previous authors, however, reported an average calf age of 19 weeks and 200 kg weight at harvest. Similarly, Wilke et al. [20] reported a mean axial rotation at L4-5 of $1.3^\circ$ in their bovine lumbar spine model. Again in their series, the average calf age at spine harvest was 16 weeks with an average subject weight of 179 kg. In our study population, the average calf age was less than 2 weeks with an average calf weight of 50 kg. The diminutive size and mass of the spines in our test series is likely responsible for the slightly increased rotation recorded in our series. Clearly the specimen size and mass in other authors’ series would not accurately model a small statured pediatric population. Rather, we propose that our mean calf weight of 50 kg more closely simulates a smaller juvenile human spine.

After creation of bilateral defects, we recorded an increase in axial rotation at L4-5 to $9.2^\circ$. This result again compares favorably to the results of previous authors who noted an increase in L4-5 axial rotation to $8.01^\circ$ from an intact spine baseline mean of $3.3^\circ$ [17]. In our series no construct type returned axial rotation at L4-5 to baseline values. In terms of rank order efficacy, however, the titanium miniplate ($M=5.6^\circ, SE=1.1$) was more effective than the cable plate method ($M=6.9^\circ, SE=1.1$), which was more effective than the pedicle screw hook rod device ($M=7.2^\circ, SE=1.1$). While the above differences did not demonstrate statistical significance, the aggregate reduction in mean of all methods combined was significantly different than the mean of all destabilized. In previous comparisons of technique [17], a modified Scott’s technique — pedicle screw with wire loop around the lamina — was noted to reduce rotation more so than hook rod, Buck and classic Scott’s technique — transverse process/laminar looped wire. Ulibarri et al. reported stiffness data (Nm/°) rather than angular displacement (degrees axial rotation) after repair of the spondylolytic defect. They rank ordered repair stiffness in axial rotation of different constructs noting that pedicle screw cable methods and an intralaminar link construct were stiffer than the intact spine, which was stiffer than a pedicle screw cable system. In their series, the Scott wiring technique was significantly less stiff than the intact spine in axial rotation [11].

Flexion-extension differences

In our series, there was no significant difference between the method of repair used and the magnitude of defect displacement measured when subjected to flexion-extension moments. Mean gap displacements when rank ordered least to most were titanium miniplate ($M=1.1\text{ mm}, \text{SE}=0.22$), pedicle screw hook rod ($M=1.4\text{ mm}, \text{SE}=0.38$), and cable plate ($M=1.5, \text{SE}=0.22$). Ulibarri et al. similarly did not find significant differences in spondylolysis gap displacement in flexion-extension testing. However, in their series an intralaminar link construct and pedicle screw hook construct were more effective than a pedicle screw cable construct [11].

Lateral bending differences

Interestingly, previous authors have not reported the effect of stabilization of the simulated pars defect subjected to lateral bending moments, confining their testing protocols to axial rotation and flexion-extension modes only [11,21]. It was in this mode of testing, however, that we demonstrated the greatest difference between the plating method and cable or hook rod technique. There was significantly less defect displacement in the titanium miniplate group with a mean displacement of 0.59 mm, then with means of 1.2 and 1.3 mm for the PSHR and cable plate methods,
respectively. Clearly, lateral bending movements are essential to activities of daily living and upon return to athletic activity. Hence, the favorable effect of miniplate fixation in this mode of loading may have a positive clinical effect.

Study limitations

With this study we have attempted to compare two novel methods of pars defect repair to a previously established gold standard stabilization method. While non-destructive testing is described, we have not analyzed the effects of cyclic loading and the capacity of these methods to withstand a million cycles of load which might be experienced during the first 3 to 4 months of bone healing.

As previously mentioned, the arch plate application in the lumbar spine is novel. It is difficult to know how much it can support within a human model. We are reserved on this. This could be a factor enhanced by the weight supported by the human L5 vertebrae. A calf L5 isthmus is large and thick with the ability to implant a plate easily. An arch plate applied along a human L5 vertebra can be more difficult with multiple screws. This further illustrates the need to proceed with human cadaveric testing.

Conclusions

Osteotomy of the pars interarticularis significantly increased intervertebral rotation in a calf spine model. The three methods of repair tested reduced rotation without definite superiority of any method. Pedicle screw hook rod and miniplate methods significantly decreased rotational ROM compared to specimens with a pars defect. In lateral bending, miniplate fixation provided better defect stabilization than pedicle screw hook rod or cable plate methods.

Disclosure of interest

A research grant in support of this work was received from Synthes Spine of approximately $5,000 USD. No other conflicts of interest exist.

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