

Biomechanical comparison between titanium and cobalt chromium rods used in a pedicle subtraction osteotomy model

Kalpiti N. Shah, Gregory Walker,
Sarath C. Koruprolu, Alan H. Daniels

Department of Orthopaedic Surgery,
Warren Alpert School of Medicine,
Brown University, Providence, RI, USA

Abstract

Instrumentation failure is a common complication following complex spinal reconstruction and deformity correction. Rod fracture is the most frequent mode of hardware failure and often occurs at or near a 3-column osteotomy site. Titanium (Ti) rods are commonly utilized for spinal fixations, however, theoretically stiffer materials, such as cobalt-chrome (CoCr) rods are also available. Despite ongoing use in clinical practice, there is little biomechanical evidence that compares the construct ability to withstand fatigue stress for Ti and Co-Cr rods. Six models using 2 polyethylene blocks each were used to simulate a pedicle subtraction osteotomy. Within each block 6.0×45 mm polyaxial screws were placed and connected to another block using either two 6.0×100 mm Ti (3 models) or CoCr rods (3 models). The rods were bent to 40° using a French bender and were secured to the screws to give a vertical height of 1.5 cm between the blocks. The blocks were fatigue tested with 700N at 4 Hz until failure. The average number of cycles to failure for the Ti rod models was 12840 while the CoCr rod models failed at a significantly higher, 58351 cycles ($P=0.003$). All Ti models experienced rod fracture as the mode of failure. Two out of the three CoCr models had rod fractures while the last sample failed via screw fracture at the screw-tulip junction. The risk of rod failure is substantial in the setting of long segment spinal arthrodesis and corrective osteotomy. Efforts to increase the mechanical strength of posterior constructs may reduce the occurrence of this complication. Utilizing CoCr rods in patients with pedicle subtraction osteotomy may reduce the rate of device failure during maturation of the posterior fusion mass and limit the need for supplemental anterior column support

Introduction

Given the advances and options available for spinal implants, surgeons are better able to address spinal pathologies and deformities of increasing complexity.¹⁻⁸ Despite the advances, however, complication rates after major spinal instrumentation remain high. They include instrumentation failure, pseudoarthrosis, junctional kyphosis proximal to the surgical construct, neurologic injury and infection.^{1,9-16} Instrumentation failure may represent an opportunity to improve surgical care as a potentially preventable complication. The typical methodology of failure is fatigue failure over time and not a single event.¹⁷

Rod fracture (RF) is the most common mode of device failure following complex spinal reconstruction.^{18,19} The longitudinal rods must provide adequate support to the instrumented spine as fusion occurs in the affected areas over the course of weeks to months. Failure at the level of these longitudinal rods may occur due to a sustained increase in motion across the fusion levels as result of delayed union or pseudoarthrosis.²⁰ Factors such as nutrition, increasing age, smoking, prior radiation and disease-modifying antirheumatic drugs (DMARDs) have been linked to an increased risk of implant failure, usually secondary to a delay or prevention of arthrodesis.^{19,21} Failure may also be seen due to improper implant placement, material selection, overbending of the rods, patient habitus which may put increased stresses across the instrumentation and accidents.²²⁻²⁴ Additionally, a pedicle-subtraction osteotomy was an independent risk factor for rod failure given the increased stresses that construct places on its instrumentation.¹⁹

Rod material has significant implications on its durability, biocompatibility and artifact production during advance imaging and should be considered carefully. The fatigue properties of a variety of metals and alloys used in spinal hardware have been subject to scrutiny.²²⁻²⁶ Clinical studies have also shown that the rates of rod fractures increase with the decreasing fatigue strength of the material being used, namely an increase in fractures were seen with titanium (Ti) rods compared to cobalt chromium (CoCr) rods and stainless steel rods after posterior spinal arthrodesis.^{19,27} Further, rod contouring performed to achieve a desired curve imparts marks onto the rods that may weaken its durability.^{23,24}

Clinical observations suggest that the most common association for pseudarthrosis was rod fracture at the PSO level. This occurs with higher frequency in cases

Correspondence: Kalpit N. Shah, Department of Orthopaedic Surgery, Warren Alpert School of Medicine, Brown University, Box G-A1, Providence, Rhode Island 02912, USA.
E-mail: kalpit210@gmail.com

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where adjacent disc spaces to the PSO level were preserved. In this situation, intact disks anteriorly with posterior nonunion at the osteotomy site results in a circumferential nonunion that leads to rod fractures.²⁸ Rod fracture can negatively impact clinical outcome by producing spinal pain, loss of deformity correction and functional compromise.^{27,29,30} This hardware complication often leads to revision spinal surgery with a negative impact on the patient and health-care system alike. Focus on preventing rod fatigue failure has the potential to improve patient outcomes.³¹

In this study, we aimed to biomechanically investigate the difference in fatigue failure seen in cobalt chromium and titanium rods in a pedicle-subtraction osteotomy model.

Materials and Methods

Six pedicle subtraction osteotomy models were constructed using lumbar bilateral ultra-high weight polyethylene (UHMWPE) test blocks as per ASTM D638 specifications. Test blocks were used to eliminate the effects of the variability of bone properties and morphometry. Each block was instrumented with two 6.5×45 mm titanium screws. The pedicle subtraction osteotomy model was created by placing a gap of 4 cm

between two polyethylene blocks and connecting them with either two 6.0 mm Ti or two 6.0 mm CoCr rods. The 4cm gap was determined by calculating the distance between L1 and L3 and subtracting the pedicle width of L2 to determine the distance L1-L3 in an L2 PSO.

The rods were bent with French benders to an angle of 40 degrees in the center prior to being placed in the screw tulip-head to simulate the angle seen at the level of a PSO. Set screws were used to tighten the rods to the screws (Figure 1). Three models were made with Ti rods and three models were constructed using CoCr rods for fatigue testing. One additional model was

made using Ti rods and tested in static compression bending to determine the load parameters (2% offset yield, ultimate displacement, and ultimate load) for fatigue testing.

A sinusoidal load was applied to the spinal constructs in fatigue testing. Loading was maintained via a constant sinusoidal load under amplitude control. A constant load ratio (R) for all tests was established and was equal 10 as recommended by ASTM F1717. Fatigue testing was conducted at 75% of the ultimate load (N). Each construct was fatigue-tested to failure at a frequency of 4 Hz of axial compression on an Instron 8521S servohydraulic test frame

(Instron; Norwood, MA). The number of cycles and method of model failure was recorded along with the mode of failure.

Results

An initial load-to-failure test of a Ti rod model required 900N for the rod to fracture. As such, a calculation was made to determine the force at which to conduct the cyclic axial compression fatigue testing – this was found to be roughly 700N (75% of 900N).

The Ti models failed at 13,200 cycles, 11,967 cycles and 13,352 cycles for an average of 12,840 cycles. The CoCr models failed at 40,902 cycles, 66,609 cycles and 29,512 cycles for an average of 45,674 cycles. The CoCr models failed at a significantly higher number of cycles compared to the Ti models ($P=0.04$) (Figure 2)

All models failed at the level of the rods – they experienced a fracture of the posterior, longitudinal rods (Figure 3).

Discussion and Conclusions

The results of this study suggest that CoCr rods have a greater resistance to fatigue than Ti rods. CoCr rods failed at an average number of cycles almost 4 times

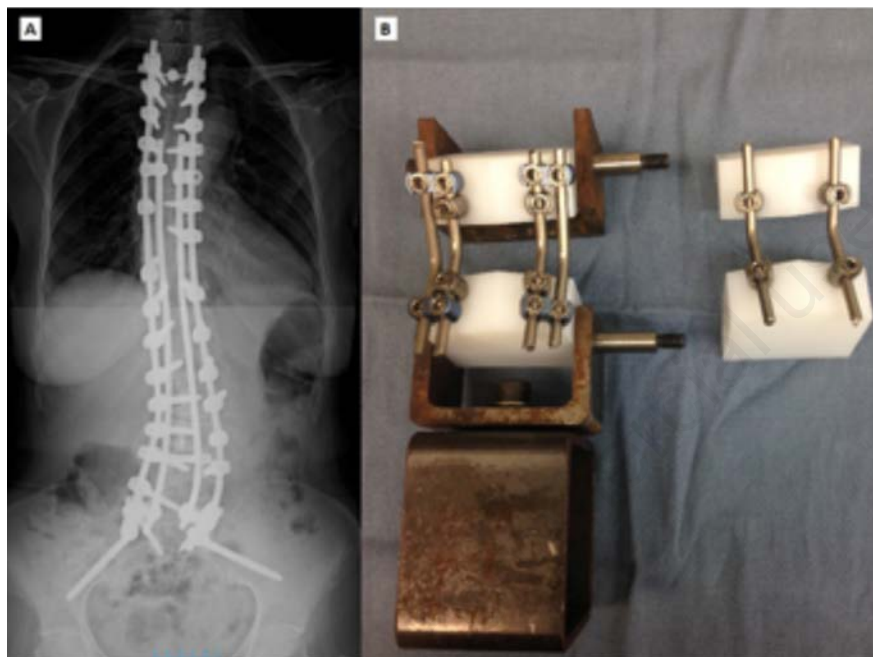


Figure 1. Model with titanium screws and titanium rods.

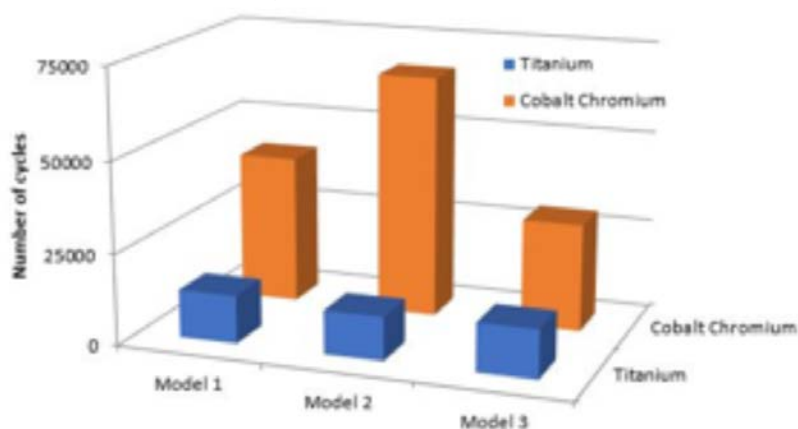


Figure 2. Number of cycles at which each of the three titanium and cobalt chromium models failed.



Figure 3. Example of a titanium model with a broken posterior titanium rod.

greater than the average number of cycles to fatigue failure for Ti rods. This data corresponds with recent literature and other studies regarding fatigue testing of orthopaedic alloys commonly used in spine fusion surgeries.^{18,22,23,25,26,32}

Nguyen *et al.* conducted a similar study using a lumbar bilateral vertebrectomy model.²⁶ Their results also demonstrated Ti rods failed at a significantly lower number of cycles than CoCr chromium rods. However, the authors also tested at lower forces than the ATSM recommended 75% of the load-to-failure force. As expected the lower forces allowed for a proportional increase in the number of cycles for both Ti and CoCr models. They also applied two points of bending by the French bender (roughly 15 degrees each, for a total of about 26-30 degrees). In contrast, we bent our longitudinal rods at the center of the construct to about 40 degrees to simulate the angles that would be seen in a pedicle subtraction osteotomy model. The higher number of bends in their model may correlate with the lower number of cycles to failure reported for both, Ti and CoCr models.

Intraoperative contouring is frequently required to accomplish adequate correction of spinal deformity. In our study, all rods were bent to 40 degrees with a French bender. Load application testing of titanium and cobalt rods in other studies have shown that the yield strength and rod bending stiffness are both decreased after contouring and the magnitude of the decrease is dependent upon the degree of the bend.^{23,25} Unless pre-contoured rods are readily available rod contouring is almost inevitable in the clinical setting. Our data illustrates that contoured CoCr rod in comparison to a contoured Ti rod can withstand significantly higher fatigue stress. Both CoCr and Ti rods have been shown to provide stable post-operative correction in flexible thoracic adolescent idiopathic scoliosis.³² However *in vitro* studies have demonstrated CoCr rods could potentially allow greater forces of correction with superior stability over time.³³ Thus CoCr may represent a more suitable option for rod material when a significant degree of contouring is needed for deformity correction.

In their retrospective study, Shinohara *et al.* found no differences in failure rate between Ti rods and CoCr rods after implantation surgery for early onset scoliosis.¹⁸ Unfortunately, their study represented a relatively small sample size of 13 patients. In addition, there are some key differences in patient demographics across the two groups compared in this study. The patients in the CoCr rod group were on average 1.4 years older than patients in the Ti rod group.

The patients in the CoCr group were significantly larger than the patients in the Ti group – both mean height and body weight were significantly greater in the older patients with CoCr rods. Therefore, the CoCr rods were under a greater stress from bearing a larger load. As admitted by the authors, this likely increased the risk for implant failure in the CoCr group, leading it to be demonstrate a similar rate of failure to Ti rods.

Shinohara *et al.* argue that despite differences in patient size, the groups were well balanced in treatment as a single surgeon operated on all the patients using the same surgical techniques.¹⁸ Although the discrepancy between the ages of the study groups could be due to random chance it begs the question of a potential underlying selection bias (*e.g.* were the stiffer CoCr rods selectively used in older, heavier patients?). Further studies that are larger, prospective and potentially blinded, may help reveal a truly unbiased result to this rather challenging question.

Similarly, Smith *et al.* prospectively analyzed a large group of patients across multiple medical centers in the United States undergoing correction of a large spinal deformity (>5 levels). They evaluated for a variety of factors associated with rod fracture in that cohort. The authors reported that a PSO was associated with rod fracture while the use of CoCr rods compared with Ti and stainless steel rods led to fewer implant failures.¹⁹ Given the high rate of rod fractures in the setting of PSO, our study biomechanically confirms the potential solution to reducing the risk of implant failure with the use of CoCr rods.

In addition to the resistance to rod fracture, CoCr rods have also been reported to provide better deformity correction in the setting of scoliosis. Lamerain *et al.* reported their outcomes on patients undergoing posterior correction and fusion for adolescent idiopathic scoliosis and reported a significantly higher correction in patients who had CoCr rods placed compared to those with stainless-steel rods used for the correction.³⁴

In conclusion, Ti rods used longitudinally in a posterior spinal arthrodesis construct with an aggressive bend fail after a fewer number of cycles than CoCr rods.

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