Biomechanical analysis of cervicothoracic junction osteotomy in cadaveric model of ankylosing spondylitis: effect of rod material and diameter

Laboratory investigation

JUSTIN K. SCHEER, B.S., JESSICA A. TANG, B.S., VEDAT DEVIREN, M.D., FRANK ACOSTA, M.D., JENNIFER M. BUCKLEY, PH.D., MURAT PEKMEZCI, M.D., R. TRIGG McCLELLAN, M.D., and CHRISTOPHER P. AMES, M.D.

1Biomechanical Testing Facility, Orthopaedic Trauma Institute, San Francisco General Hospital; and Departments of 2Orthopaedic Surgery and 3Neurological Surgery, University of California, San Francisco, California

Object. Ankylosing spondylitis (AS) is a genetic condition that frequently results in spinal sagittal plane deformity of thoracolumbar or cervicothoracic junctions. Generally, a combination of osteotomy and spinal fixation is used to treat severe cases. Although surgical techniques for traumatic injury across the cervicothoracic junction have been well characterized in clinical and biomechanical literature, the specific model of instrumented opening wedge osteotomy in autofused AS has not been studied biomechanically. This study characterizes the structural stability of various posterior fixation techniques across the cervicothoracic junction in spines with AS, specifically considering the effects of posterior rod diameter and material type.

Methods. For each of 10 fresh-frozen human spines (3 male, 7 female; mean age 60 ± 10 years; C3–T6), an opening wedge osteotomy was performed at C7–T1. Lateral mass screws were inserted bilaterally from C-4 to C-6 and pedicle screws from T-1 to T-3. For each specimen, 3.2-mm titanium (Ti), 3.5-mm Ti, and 3.5-mm cobalt chromium (CoCr) posterior spinal fusion rods were tested. To simulate the anterior autofusion and long lever arms characteristic of AS, anterior cervical plates were placed from C-4 to C-7 and T-1 to T-3 using fixed angle screws. Nondestructive flexion-extension, lateral bending, and axial rotation tests were conducted to 3.0 Nm in each anatomical direction; 3D motion tracking was used to monitor primary range of motion across the osteotomy (C7–T1). Biomechanical tests used a repeat-measures test design. The order of testing for each rod type was randomized across specimens.

Results. Constructs instrumented with 3.5-mm Ti and 3.5-mm CoCr rods were significantly stiffer in flexion-extension than those with the 3.2-mm Ti rod (25.2% ± 16.4% and 48.1% ± 15.3% greater than 3.2-mm Ti, respectively, p < 0.05). For axial rotation, the 3.5-mm Ti and 3.5-mm CoCr constructs also exhibited a significant increase in rigidity compared with the 3.2-mm Ti construct (36.1% ± 12.2% and 52.0% ± 20.0%, respectively, p < 0.05). There were no significant differences in rigidity seen between the 3 types of rods in lateral bending (p > 0.05). The 3.5-mm CoCr rod constructs showed significantly higher rigidity in flexion-extension than the 3.5-mm Ti rod constructs (33.1% ± 15.5%, p < 0.05). There was a trend for 3.5-mm CoCr to have greater rigidity in axial rotation (36.2% ± 18.6%), but this difference was not statistically significant (p > 0.05).

Conclusions. The results of this study suggest that 3.5-mm CoCr rods are optimal for achieving the most rigid construct in opening wedge osteotomy in the cervicothoracic region of an AS model. Rod diameter and material properties should be considered in construct strategy. Some surgeons have advocated anterior plating in patients with AS after osteotomy for additional stability and bone graft surface. Although this effect was not examined in this study, additional posterior stability achieved with CoCr may decrease the need for additional anterior procedures.

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Key Words • spine biomechanics • cervicothoracic kyphosis • ankylosing spondylitis • opening wedge osteotomy • rod diameter • cobalt chrome versus titanium

ANKYLOSING spondylitis is a genetic disorder that may result in significant pain and progress to rigid spinal deformity. It can affect all areas of the spine, causing thoracic kyphosis, increased flexion in the cervicothoracic region, and flattening of lumbar lordosis, leading to fixed sagittal imbalance and loss of horizontal gaze. Surgical treatments such as an opening wedge osteotomy and pedicle subtraction osteotomy have been used to successfully correct the fixed imbalance. Generally, a combination of osteotomy and spinal fixation is used to treat severe cases of AS to restore spinal stability. Supplementary second-stage anterior grafting has not been routinely necessary in these patients because they typically form bone quite well.

Although surgical techniques across the cervicotho...
racic junction have been biomechanically characterized in traumatic instability and clinical outcomes have been reported for opening wedge osteotomy.\textsuperscript{11,12,14} The effect of rod diameter and rod material has not been directly investigated for this area of the spine specifically in AS. There have been studies in which the rod diameters were varied, but for other areas of the spine.\textsuperscript{8,16,28,42} In addition, the studies that have looked at the differences in rod material properties have focused on Ti and stainless steel\textsuperscript{33,34,36,42,44,45} and not the newer CoCr alloys. Despite these studies, the best reconstruction technique to restore optimal rigidity across the destabilized osteotomy region remains unclear.

The goal of this study is to characterize the structural stability of various posterior fixation techniques across the cervicothoracic junction in a cadaveric model of simulated AS by comparing the multidirectional bending rigidity of these constructs as a function of 1) rod diameter and 2) rod material, specifically comparing a CoCr alloy with Ti. Biomechanical testing was performed on cadaveric head-neck specimens using a repeated-measures test with Ti. Biomechanical testing was performed on cadaveric head-neck specimens using a repeated-measures test design with each of 3 different surgical configurations being used in each specimen. Outcome measures from this study included primary (on-axis) and secondary (off-axis) ROM in each of the 6 anatomical bending directions.

Methods

Specimen Preparation and Treatment Groups

Ten fresh-frozen human spines (3 male, 7 female; mean age 60 ± 10 years; C3–T6) were procured for this study. Anterior-posterior and lateral radiographs were obtained in each specimen prior to full dissection to confirm normal anatomy and lack of metastatic tumors. Standard lateral dual x-ray absorptiometry (DEXA) scans were taken of each specimen with the C6–T2 region mapped as L1–4 on the DEXA scanner’s internal software (Hologic QDR-2000, Hologic, Inc.). The data provided a relative measurement of bone mineral density within the specimens but could not be used to determine the clinical degree of osteoporosis because the cervicothoracic spine is not a standard density assessment site.

Following radiographic assessment, the spinal sections were cleaned of muscles and connective tissue, with care taken not to disrupt ligaments and intervertebral discs. The cranial- (C-3) and caudal-most (T-4) vertebrae were potted to three-fourths axial depth in a polymer casting agent (Smooth Cast 300, Smooth-On) to facilitate rigid fixation to the test frame during biomechanical testing.

To simulate the autofusion from bridging syndesmophytes and long adjacent lever arms of the AS spine, anterior cervical plates were placed from C-4 to C-7 and from T-1 to T-3. For each specimen, an opening wedge osteotomy was performed at C7–T1 (Fig. 1). A disectomy of the C7–T1 disc including the lateral anulus and sparing the posterior longitudinal ligament was also performed. The osteotomy included a partial C-6 and partial T-1 laminectomy and a complete C-7 laminectomy and pediculectomy. Lateral mass screws (3.5 × 16 mm) were inserted bilaterally from C-4 to C-6; pedicle screws (4.5 × 30 mm) were inserted bilaterally from T-1 to T-3; and 3 different types of rods were tested—namely, 3.2-mm Ti, 3.5-mm Ti, and 3.5-mm CoCr. All the instrumentation and insertion tools were standard (provided by Medtronic). The order of testing for each rod type was randomized across specimens to minimize bias due to tissue fatigue.

Multidirectional Bending Rigidity

Multidirectional bending tests were conducted on each spinal section for each of the aforementioned rod types using a cable-driven pure moment testing apparatus\textsuperscript{11,12,14} mounted to a uniaxial hydraulic press (858 Mini Bionix, MTS Systems). Briefly, this system functions by inducing a pure moment (or force-couple) at the top of the specimen via a circular loading ring. A single cable is wound around the ring, and tensioning this cable applies the force-couple. Tension levels are controlled via the throw of the uniaxial hydraulic actuator, and applied moment is calculated as a function of the loading ring size and the cable tension as measured by the uniaxial load cell mounted to the hydraulic actuator. The cable can be wound in different directions on the loading ring to induce flexion-extension, right/left lateral bending, and right/left axial rotation of the entire spinal segment. To ensure that pure moment loading conditions were induced throughout each test, the validated 3D sliding ring setup\textsuperscript{14} was used, consisting of an x-y and rotary bearing table at the base of the test frame and a counter-balanced loading ring on vertical bearings (Fig. 2 left).

During the bending tests, relative motion across the osteotomy site (C7–T1) was measured using 3D motion tracking (Optotrak 3020, Northern Digital). Rigid body markers (each consisting of 3 individual infrared sensors) were rigidly attached to the C-7 and T-1 vertebrae via cervical lateral mass screws (3.5 × 16 mm, DePuy) placed anteriorly in the vertebral body (Fig. 2 right). These screws were positioned so as not to interfere with reconstruction hardware, and this was confirmed following each surgery using planar radiographs (Philips BV Pulsera). Relative motion of the vertebrae was tracked in real-time from the
3D camera system using custom-designed software (Flex-Win 2008, Barrow Neurological Institute), which has a validated accuracy of 0.1° for spinal testing.11,12

Nondestructive flexion-extension, lateral bending, and axial rotation tests were performed on each specimen in accordance with a standard protocol.11,12 Specifically, specimens were preconditioned in each test direction by applying 3 cycles of 0–1.5 Nm at 0.02 Hz, followed by a 60-second hold at 0 Nm. Following preconditioning, specimens were quasi-statically loaded in increments of 0.75 Nm every 45 seconds to a maximum of 3.0 Nm. Loading conditions were determined as an intermediate between physiological loads experienced by the cervical spine and the lumbar spine. Therefore, the choice of 3 Nm as the upper end moment was derived from an intermediate value between the 7.5-Nm physiological load experienced in the lumbar spine11 and the 1.5 Nm physiological load experienced in the cervical spine.30 3 Nm is on the lower end of an intermediate value between the 2 extremes, but priority was taken to apply a large enough load to yield noticeable ROM differences without inducing destruction and compromising physiological conditions.

**Outcome Measures**

Multidirectional bending rigidity was compared across the fixation constructs for the motion segment C7–T1 (across the osteotomy site) using 2 metrics: 1) maximum range of motion in the primary loading direction (primary ROM), and 2) maximum coupled motion—for example, lateral bending during axial rotational loading (off-axis ROM). Statistical analyses were performed using commercially available software (JMP v5.0, SAS Institute, Inc.). A repeated-measures ANOVA with pairwise comparisons was performed; the Student t-test with the Tukey post hoc adjustment was used to analyze differences in ROM across all constructs. The level of significance for all statistical tests was set at p < 0.05.

**Results**

Significant differences in primary ROM between different testing configurations are presented graphically in Fig. 3.

**Rod Diameter**

Constructs instrumented with 3.5-mm Ti and 3.5-mm CoCr rods exhibited a significant increase in rigidity compared with the 3.2-mm Ti rod during flexion-extension (25.2% ± 16.4% for Ti and 48.1% ± 15.3% for CoCr, p < 0.05 for both). For axial rotation, the 3.5-mm Ti and 3.5-mm CoCr constructs also exhibited a significant increase in rigidity compared with the 3.2-mm Ti rod (36.1% ± 12.2% for Ti and 52.0% ± 20.0% for CoCr, p < 0.05 for both). There were no significant differences in rigidity seen between the 3 types of rods in lateral bending (p > 0.05) and between the 3.2- and 3.5-mm rods for the coupled motion in all bending directions (p > 0.05).

**Material Type**

The 3.5-mm CoCr rod constructs showed significantly higher rigidity in flexion-extension compared with the 3.5-mm Ti rod constructs (33.1% ± 15.5%, p < 0.05). Although there was a trend for 3.5-mm CoCr to have greater rigidity in axial rotation (36.2% ± 18.6%), this difference was not statistically significant (p > 0.05). There was no significant difference in coupled motion between the 3.5-mm CoCr and 3.5-mm Ti constructs, with the exception of lateral coupled bending during flexion-extension, with the CoCr construct showing less coupled motion (p < 0.05).

**Discussion**

The results of this study suggest that 3.5-mm CoCr rods are optimal for achieving the most rigid construct in cases of opening wedge cervicothoracic extension osteotomy in AS. In addition, they indicate that rod diameter and material have significant effects on construct rigidity after osteotomy.

Considering just the posterior rods themselves and applying Euler beam theory, the bending stiffness of a 2-rod system in the flexion-extension direction is directly proportional to the fourth power of the rod diameter.29 The increase in rod diameter from 3.2 mm to 3.5 mm (approximately 10%) would thus correspond to a 43% increase in bending rigidity in the flexion-extension direction. In lateral bending and axial rotation, the offset between the rods in the transverse plane largely dictates the bending rigidity of the system, with a larger offset corresponding to increased stiffness. Applying Euler beam theory and the parallel axis theorem and assuming that the offset between the rods is an order of magnitude greater than the individual rod diameters, the expected increase in bending rigidity with rod diameter is proportional to the ratio of the different rod diameters to the second power.29 Thus, the same 10% increase in rod diameter from a 3.2-mm to a 3.5-mm rod results in a 21%
increase in bending rigidity in these 2 loading modes. For all loading modes, the bending rigidity is directly proportional to the elastic modulus of the rod material. A change in rod material from Ti (elastic modulus of 116 GPa)\textsuperscript{17} to CoCr (218 GPa)\textsuperscript{17} would cause an expected 87% increase in stiffness.

In reality, the change in bending rigidity experienced by the entire bone-implant system across the fusion site does not exactly correspond with the aforementioned engineering calculations. Other factors besides the rod geometry and material properties affect the rigidity—which is demonstrated by an increase or decrease in multiaxial ROM. Specifically, the compliance of the interface between the rods and the pedicle or lateral mass screws and also the compliance of the screw-bone interface will affect the overall rigidity of the system. In addition, differences in “intraoperative” contouring between rod types will also affect construct rigidity. In most instances, it can be expected that changing the rod type would actually result in a smaller change in construct rigidity than calculated engineering principles indicate. This is due to both the limited sensitivity of our experiment (ROM resolution of 0.1°)\textsuperscript{11,12} and the relatively low compliance of the anatomical tissues relative to the metal implants. Both of these factors will mitigate the ROM differences that each rod can be expected to exhibit.

In addition to CoCr being a stiffer metal than Ti, another advantage of CoCr over Ti lies in CoCr’s property of being less notch sensitive. It has been well established that the fatigue strength of Ti posterior fusion rods is substantially decreased by intraoperative contouring,\textsuperscript{22} which is necessary for implementing cervicothoracic fusion constructs in patients with AS. The reduced notch sensitivity of CoCr, as shown in previous studies, and its increase in stiffness for stabilizing the spine, as our study indicates, both represent large benefits to be considered.

To our knowledge, no biomechanical studies to date have addressed the issue of rod diameter and material properties for stabilizing the spine in cases of AS. However, with respect to varying rod diameter, our results are similar to the results obtained by Polly et al.\textsuperscript{24} in the lumbar spine and Tatsumi et al.\textsuperscript{38} in cervicothoracic constructs. In their studies the larger-diameter rods were significantly stiffer than the smaller-diameter rods. As for CoCr, our results indicate that CoCr is stiffer than Ti, which is consistent with the literature as well.\textsuperscript{17}

There are differences in the way the osteotomy was performed between this study and clinical practice. In more detail, the C7–T1 opening wedge osteotomy was simulated in the cadaver model via an anterior discectomy approach with hinging on the posterior longitudinal ligament at the disc space. In our clinical practice, the osteotomy is performed differently for a number of reasons. First, the discectomy; because this osteotomy type is most commonly used in AS. Second, the osteotomy is performed from an all-posterior approach because most of these patients have significant fixed cervical kyphosis and an initial anterior approach is not possible. Clinically, we use the approach described by Simmons et al.\textsuperscript{35} with a C6–T1 laminectomy, C-7 pediculectomy as required for foramin decompression, and a controlled extension osteoclasis across the ankylosed C7–T1 disc space resulting in an opening wedge at the site of anterior cortex or bridging osteophyte fracture.

This study has several strengths. First, the experimental design allowed examination of micromotion across the osteotomy site under multiaxial bending conditions to an accuracy of 0.1°.\textsuperscript{11,12} Both primary and off-axis motions were considered, as was the propensity of rod diameter and material properties to affect the spinal ROM. Moreover, the repeated-measures test design, used for data analysis, controls for donor effects by having each specimen serve as its own control.

This study also has a few limitations. Because this is a cadaver study, the bending loads applied and the lack of active muscles are not physiologically exact. Also, because we used a repeated-measures test design, the randomized specimens likely became more flexible in later tests due to repeated testing. However, the order in which the different rods were instrumented into the specimens and tested was randomized to minimize bias due to tissue fatigue. Moreover, this study simulates only the immediate postoperative condition and does not evaluate the effect of fatigue on the construct and more importantly, at the screw-bone interface. It would be logical to assume that stiffer rods (large diameter or stiffer alloys) would place additional stress on the fixation points. Clinically, additional points of fixation, bicortical placement, or cervical pedicle screw placement may be beneficial. Further fatigue tests would allow assessment of possible failure mechanisms within these constructs.

Conclusions

Varying rod materials and diameters had significant effects on construct rigidity in this simulated model of AS, in which opening wedge osteotomy was performed at the cervicothoracic junction. Use of 3.5-mm CoCr rods yielded substantially stiffer constructs in ROM testing than Ti rods of the same diameter. There is increasing use of CoCr and varied rod diameters for the treatment of spinal deformity of the thoracolumbar spine. In many centers, CoCr has become the metal of choice due to favorable stiffness, fatigue characteristics, notch resistance,
and yield point (for in situ bending). Although increased rod diameters and stiffer metals may be thought to predictably result in increased construct rigidity, the significance of this increase in various loading modes is indication specific. Without directly determining the magnitude of the potential benefit in terms of increased stiffness, it would be difficult to determine whether it is worth using a new rod size or metal for a specific clinical situation. We have therefore investigated one of the more common complex cervical deformity indications in this simulated biomechanical model and demonstrated a potential advantage of a novel rod material for this type of application. This information may be valuable to the clinician in planning reconstruction strategies in this challenging patient population but should be considered along with force of correction, regional and global balance achieved, fixation integrity at the screw-bone interface, and the likely bone-forming potential of the patient in deciding whether to perform supplementary anterior grafting and plating.

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Address correspondence to: Justin K. Scheer, B.S., UCSF/SFGH Orthopaedic Trauma Institute, Department of Orthopaedic Surgery, University of California, San Francisco, San Francisco General Hospital, 1001 Potrero Avenue, Building 9, 3rd floor, San Francisco, California 94110. email: jscheer@ucsd.edu.