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A Literature Review on Spinal Rod Surgery in Scoliosis Clinical Indications and Complications

Amirhossein Rahmani[1*], Aliakbar Razavi Tanha[2], Saman Ghedasati[2]

[1] Department of Plastic and Reconstructive Surgery, Iranshahr University of Medical Sciences, Iranshahr, Iran (Amirho.rahmani@gmail.com)

[2] Islamic Azad University, Tehran Medical Branch, Tehran, Iran

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Abstract

For adolescent idiopathic scoliosis (AIS) patients, the surgical treatment entails multisegmented pedicle screws connected by contoured bilateral rods. The rods are subjected to significant corrective stresses, and their ability to bear these pressures without permanent deformation depends on their biomechanical characteristics. These characteristics, in turn, are influenced by the rod's material, diameter, and form. A particular biomechanical silhouette is required in the surgical treatment of AIS, which differs significantly from the shape necessary to correct adult deformities. The purpose of this study is to review current knowledge of rod biomechanics concerning unusual rod constructions, intending to bridge the gap between biomechanical investigations and clinical relevance in AIS patients through translational research.

Keywords*:* Neurosurgery; Scoliosis; Spinal fusion; Surgery; Adolescent.

Introduction

Adolescent idiopathic scoliosis (AIS) is challenging to treat surgically due to the necessity for three-dimensional (3D) correction of the spine and its fusion while avoiding intraoperative complications such as pedicle fractures, dural rips, severe bleeding, and neurological deficits relating to the spine [1,2]. The procedure whereby AIS patients are treated surgically usually involves the placement of a posterior multisegmental pedicle screw in the length of the desired fusion [3]. As a result of the deformity, different treatment methods may be used including translated manipulation, distraction-compression, rod derotation, direct derotation of the vertebra, cantilever, in situ bending, or vertebral co-planar alignment. Pedicle screws attached to twin rods are one common treatment method employed to correct such deformities [4-7]. To achieve a balanced spine with a natural lordosis/kyphosis profile [8], the rods are bent to the correct sagittal shape before being inserted. This is the secret to the intraoperative correction procedure's success.

Rod biomechanics play a large role in maneuvers since they put a great deal of stress on the rods [9].

The low viscoelasticity of the tissue means that corrective pressures, due to the tissue's low viscoelasticity, increase the risk of deforming the rod in plastic ways and consequently losing the modification. Several factors contribute to clinical outcomes with AIS surgery. These include stresses placed on the rods by the contouring and pressures and torques applied during the procedure. Despite significant studies into the advantages and drawbacks of various rod constructions, there is no consensus on the best biomechanical characteristics [10]. Preoperative hyperkyphosis is common in AIS patients, and restoring sagittal alignment has increased awareness in contemporary years [11-13]. All-pedicle screw constructions have been linked in several studies to a loss to correct thoracic kyphosis to a standard span after surgery [14]. Hyperkyphosis after surgery can raise the likelihood of neighboring segment illness and worse quality of life; thus, it is better to be a significant priority while operating. Corrective maneuvers have been blamed for the absence of kyphosis repair, linked to the construction’s biomechanical characteristics [15].

In AIS surgery, the purpose is to correct the deformity while maintaining a proportionate spine with status shoulders and avoid arc worsening [16,17]. On the other hand, the existing method is to increase the pedicle screw thickness to promote burden-sharing and more substantial rod construction to minimize rod distortion and failure of revision in the axial, sagittal, and coronal planes [18]. It was primary biomechanical research that drove this development, as there was a direct correlation between the application of this theory and the discipline's long-term viability [19]. However, advanced construct immobility may have unintended consequences. A greater proportional burden is transmitted to the rod when the implant-bone attachment improves, which reduces physiological pressure on the bone. Even though there is no evidence to indicate this notion has been confirmed in actual AIS patients in the past, it may have a long-term impact on bone quality. Furthermore, increasing the rod stiffness may increase junctional tension on tiers adjacent to the instrumentation, potentially resulting in adjacent components rupturing or decompensating beyond the implant [19,20]. The rod's form, diameter, and content characteristics heavily influence its biomechanical profile. As discussed in this outline, this approach could be used in clinical practice to treat AIS due to its potential benefits and drawbacks.

Properties of the Biomechanical System

The yield strength and stiffness of spinal rods are generally used to distinguish their biomechanical characteristics. The yield strength, often known as the yield stress, is the tension at which permanent deformation occurs [21]. Stiffness or rigidity is the ability of an object to resist deformation when it is applied with force. The elastic modulus, also known as Young’s modulus, is a method of measuring elasticity [22]. A typical rubber band, which takes relatively little force to distort (low stiffness), while significantly larger tension for enduring deformation, exemplifies the contrast between yield stability and stiffness (high yield strength) [23]. While specific material characteristics may be quickly evaluated in a lab environment, the theoretical implications may not always be applicable in practical practice. Likewise, Ayers et al. discovered that the detailed content of a particular rod could be susceptible to variations in manufacturing since unique characteristics for the same material differed considerably between manufacturers [20]. Pienkowski et al. found that implant type, rather than material, explained implant fatigue life, counting to the difficulty of interpreting rod content profile.

Rod Material

Ultrahigh strength stainless steel (UHSS), (SS) cobalt-chromium (CoCr), and titanium alloy (Ti) are the many commonly written rod textiles utilized in AIS correctional surgery. In general, Ti has a higher yield strength than SS, UHSS, and CoCr, although it has a lesser stiffness. Although CoCr has recently been used in AIS surgery, it is indicated by increased stiffness and subordinate result strength. Because of its outstanding erosion resistance, biocompatibility, and magnetic resonance imaging (MRI) compatibility, Ti was initially popular in adult and juvenile spine disfigurement surgery [23-25]. In an animal model, some studies looked at MRI artifacts among SS, Ti, and CoCr and result that Titanium rods had minor small artifacts, followed by cobalt-chromium, while stainless steel had the most [23]. Albeit Trammell et al [26] and Ahmad et al [27] showed that the dissimilarity in artifacts between CoCr and Ti did not impede the assessment of the spinal canal and encompassing neuronal components, further investigations have confirmed similar findings [27]. Although the therapeutic implications of this difference have not been proven, it has been claimed that Ti produces much higher overall diagnostic quality [27-29] compared to SS. Serhan et al [30] compared CoCr, Ti, SS, and UHSS in biomechanical research. Rods that can bend just in a plane were shaped and put in an artificial spine measure to mimic spinal malformation repair. Ninety percent of Ti rods preserved their original shape after being removed from the build, compared to 54 percent, 63 percent, and 77 percent for CoCr, SS, and UHSS, respectively, demonstrating the inferior outcome strength of the latest textiles. In contrast, UHSS and CoCr had 42 percent larger corrective forces than Ti when measured in construction because of their increased stiffness.

Rod contouring is used in AIS surgery to replicate the sagittal shape, including a lumbar lordosis pursued by a thoracic kyphosis within the expected span. The “notch effect” occurs when the rod is bent intraoperatively, causing notches or cuts in the textile, lowering the rod’s persistence boundary [31]. Slivka and colleagues [32] in response to repetitive bending, CoCr had a 25 percent higher endurance limit than UHSS, SS, or TI, according to Noshchenko et al.33, while Ti rods had the most potent “spring-back” (or yield strength) when compared to SS. In a bovine model, Wedemeyer et al [34] found that Ti rods can resist more heightened tensions and yield than the comparatively frangible SS before failing after flexing. On the other hand, Lindsey et al [35], found that Ti had a shorter fatigue life than SS in reaction to turning. Burger et al [36] simulated a physiological environment by 3-point bending SS and Ti rods and storing them for eight months at 37°C temperature. For a 300-mm rod, Ti rods yielded 6° of correction for a year, which was significantly more than SS rods. The relevance of rod textiles in AIS cases has been studied in a few clinical investigations. In a study of 90 AIS patients, Lamerian et al [37] showed that CoCr rods provided:

- Considerably more satisfactory coronal angle correction.
- Minor loss of discipline.
- Improved kyphosis rehabilitation than SS rods.

Utilizing hybrid constructs, Angelliaume et al.38 discovered which coronal arc modification was identical for CoCr and Ti constructs, whereas the CoCr group had more remarkable kyphosis restoration. Using 5.5-mm UHSS, Cidambi et al [39] discovered that the rod on the concave side of the curve flattened by 21° 4–6 weeks after surgery, similar to Salmingo et al [39] findings of 16° deformation of Ti rods. Even in stiff 5.5-mm CoCr constructions, postoperative 3D rod deformation is expected, according to Le Navéaux et al [40].

Profile and Rod Diameter

To obtain the necessary biomechanics in each given scenario, surgeons can use rods of various sizes. The fourth power of a difference in radius affects firmness [40]. As a result, curving firmness rises from 5.17 EI (Nm2) for a 5.5 mm rod to 9.18 EI (Nm2) for a 6.35 mm rod. As a result, a change in rod diameter will inevitably affect a more rigid structure, but whether this is advantageous to AIDS cases is a critical question.

In a study of 93 AIS patients, Huang et al [41] minded no disparity in curve modification, failure of discipline, or global coronal symmetry while using 5.5-mm Ti rods vs. 6.35-mm. Liu et al [42] declared an equivalent coronal curve modification of single thoracic curves; nevertheless, the authors observed that the 6.35-mm rods substantially improved kyphosis. In 116 AIS patients, Abul-Kasim [43] saw that coronal modification was not different, but kyphosis derotation and restoration with larger diameter rods were more satisfactory. Fletcher et al [44] followed up 214 AIS patients for two years and then discovered that in groups of 6.35 mm and 5.5 mm, 72 percent vs. 47 percent of the patients had average kyphosis. As opposed to previous research, another study examined 163 patients with pediatric scoliosis from a national database and discovered that the group with 5.5 mm had considerably better curve rectification two years after surgery than the 6.35 mm group. The diameter of the rod has no bearing on the correction of the sagittal plane. This study did not account for the material creating the rods, and the cohort also contained patients who were not diagnosed with AIS45.

A few studies have investigated the probable advantages of utilizing a non-circular rod in recent years. Cui et al [46] discovered that when a cross-section region is squared vs. circular, the axial immobility increases by roughly 2.5 percent, and the maximum amount of stress decreases up to 22 percent in a biomechanical simulation. In 129 AIS patients, Gehrchen et al [17] observed quick curve rectification when studying the difference between circular and "beam-like" rods. The beam-like group had a 9 percent higher rate of coronal curve correction. There was a failure to cure thoracic kyphosis in both groups, although there was no meaningful difference between them.

Hybrid Rods or Constructs

Proximal junctional kyphosis (PJK) is an aberrant kyphosis and occurs in response to fusion at the upper instrumented vertebra. It is a rather typical occurrence following surgery for AIS deformity. It has often been seen as a poor result. [47-49] PJK has been linked to several issues, including posterior ligament disruption, imperfect postoperative sagittal alignment, and applying all-pedicle screw constructions. It has also been proposed that increased rigidity in the construction will cause higher junctional pressure in the neighboring upper component, resulting in forwarding deterioration and eventually developing into PJK. Han et al [50] discovered that utilizing multiple-rod CoCr vs. 2-rod Ti to raise the stiffness of the construct improved the proportion of PJK considerably.

Han et al [51] discovered that individuals who underwent CoCr rods rather than Ti rods were more likely to develop PJK. We must consider that these investigations have been carried out on adult patients with deformities, who generally have differences in many aspects from AIS patients.

Table1. key aspects of spinal rod surgery in scoliosis

Aspect	Details	Relevant Findings/Studies
Rod Materials	Stainless Steel (SS), Ultrahigh Strength Stainless Steel (UHSS), Titanium (Ti), Cobalt-Chromium (CoCr)	Ti has better MRI compatibility and higher yield strength but lower stiffness compared to SS and CoCr. CoCr provides higher stiffness and greater correction forces. Ti has less artifact impact in imaging. [24], [25], [26], [30]
Biomechanical Properties	Yield strength, stiffness (Young's modulus)	Ti rods show greater yield strength, but lower stiffness compared to SS and CoCr. CoCr and UHSS exhibit higher stiffness and corrective forces, leading to better spinal corrections, especially in coronal and sagittal planes. [21], [23], [37]
Rod Diameter	5.5 mm vs. 6.35 mm	Larger diameters (6.35 mm) provide better correction of sagittal alignment, but studies indicate no significant difference in coronal correction between the two diameters. [41], [42], [43]
Impact of Rod Shape	Circular vs. beam-like cross-section	Beam-like rods provide a small improvement in axial stiffness and reduction in stress compared to circular rods. No significant difference in correcting thoracic kyphosis was found. [46], [17]
Hybrid Constructs	Use of multiple rod materials and combinations of pedicle screws and hooks	Hybrid constructs using CoCr and Ti rods may provide better kyphosis restoration. Use of hooks and transition rods helps reduce stiffness at the upper levels, reducing the risk of proximal junctional kyphosis (PJK). [50], [51], [56]
Shape-Memory Rods	Nitinol (Nickel-Titanium) shape-memory alloys	Shape-memory rods show promise in gradually compensating for the viscoelasticity of tissues, reducing deformation over time. However, clinical trials indicate no significant differences in outcomes compared to standard rods. [58], [60], [62]
Clinical Outcomes	Curve correction, revision rates, PJK incidence	Stronger rods (CoCr, UHSS) tend to provide better correction in adolescent idiopathic scoliosis, but increase the risk of PJK. Ti rods provide better flexibility and fewer junctional issues. Revision surgery is rare in adolescent cases. [37], [61]

Some research has investigated whether incremental reduction of stress at the construct's proximal level could lessen the rate of PJK. Lange et al [52] compared the use of cerclage wires in the proximal portion to an all-pedicle screw build of a short lumbar fusion. Segment stiffness was reduced by around 60% at the proximal transition. Facchinello et al [53] reported similar results, and Thawrani et al [54] employed proximal hooks with decreased stiffness at the upper level of the instrumented area, placing slighter pressure on the anchors. Using computer simulation, Cahill et al [55] found that utilizing a transition rod with a close diameter drop results in reduced angulation of the disc than a typical build. Theoretically, maximum implant stress could be lowered by up to 60%. Ohrt-Nissen et al [56] used this approach in a clinical environment, showing that in AIS correctional surgery utilizing two transition rods helps for better kyphosis restoration than a typical build. However, it is unknown if the new recent rod design will lessen the PJK's occurrence.

Metal Rods with Shape Memory

Some writers argue that the stiffness of the implant has little therapeutic significance because the stiffest implant currently available has a stiffness that considerably surpasses the requirement for stable fusion. During the modification process by lowering the highest load on the screw anchors. some have proposed employing variable, flexible rods to help prevent the surrounding disc from degenerating and also exposing the patients to PJK [57]. (Nitinol (a nickel-Ti) is a shape-memory metal (SMM) that can regain form after significant contortion and revert to a previously arranged form when heated further than its transition temperature, for example, body temperature [58,59]. These recovery characteristics of the rods could be advantageous since they deal with cumulative and consistent modifying pressure that can gradually compensate for the tissue's low viscoelasticity, which causes rod flattening. SMM rods have been used in scoliosis surgery in a few clinical investigations. Wang et al. [60] found that employing only a short-term SMM rod in the course of the surgery to rectify the deformity before substituting it with a rigid rod produced satisfactory results. in a new controlled randomized clinical pilot research, SMM rods were documented as the ultimate AIS patient treatment. At a 5-year follow-up, the researchers identified no differences in sagittal or coronal characteristics in comparison to regular rods, concluding that the SMM rods are effective and safe for AIS correctional surgery.

Discussion

Numerous neuro-based reviews have explored various aspects of brain health and surgery, including neurological findings associated with neuroimaging, neurological impacts of spinal deformities, and advancements in spine-related procedures [10, 61]. These reviews typically focus on the neurological outcomes, rehabilitation, and overall patient well-being following spine surgeries. However, there has been relatively little focus on spinal rod surgery specifically in the context of scoliosis, particularly concerning its clinical indications and associated complications. While neuro-based studies provide valuable insights, there remains a gap in the literature that addresses the biomechanical and clinical intricacies of rod-based corrective surgeries for scoliosis, which are critical for improving patient outcomes and minimizing post-operative complications. This review aims to address that gap by providing a comprehensive analysis of spinal rod surgery in scoliosis, emphasizing the clinical indications and complications associated with this procedure.

The patient variables (such as BMI, and skeletal maturity), curve type, choice of rods, and surgical method, influence the eventual outcome of AIS surgery. The surgical treatment of AIS differs significantly from surgery for adult deformities, and as a result, the rods' suitable biomechanical qualities differ. There is a wealth of biome information in the literature. Biomechanical research on various implant types abounds in the literature; however, there are only a few remarkable clinical trials for patients with AIS compared to implants [62]. AIS correction surgery, in comparison to adult deformation patients, has a high fusion rate, and revision surgery is uncommon. As a result, a rod's long-term durability may be limited in clinical application.

Although the increased tolerance force of Ti lessens the likelihood of fracture in the rod, in theory, the consequence is essentially non-existent in patients with AIS. It must not be the primary consideration when choosing a rod. When evaluating the 20-fold lower Young Modulus of high-stiffness rods, another study explored the theoretical drawback of employing them. This mismatch could cause bone resorption and poor osteointegration by reducing stress on the interface of bone-implant (stress shielding) [63]. While this notion may hold in an aged population, it has yet to be shown clinically in AIS surgery. The fundamental purposes of sagittal restoration and curve modification appear to be accomplished better with a more rigid build which, via intraoperative contouring, is less susceptible to weakening; this is presumably why CoCr and larger-diameter rods are becoming more popular [64]. However, high-quality research on the subject is required before any strong conclusions can be made. In addition, we recommend further research into the effectiveness of individually fitted rods bent during the production steps to reduce the weakening of the rods during intraoperative contouring.

Conclusion

Current clinical research evaluating the biomechanical differences among various rod constructions in spinal surgery for adolescent idiopathic scoliosis (AIS) remains limited by poor methodological quality and a significant risk of bias. Despite the wide use of different rod materials and designs, the overall curve correction outcomes do not appear to show significant variance across rod types. However, firmer rod constructions have demonstrated improved capacity in restoring the sagittal profile, which is a critical aspect of scoliosis correction. Additionally, innovative designs such as shape memory rods and transition rods offer the potential to reduce junctional stress, yet their long-term clinical effectiveness and broader therapeutic application remain uncertain. Further high-quality, unbiased research is essential to better understand the biomechanical and clinical implications of these novel rod technologies and to establish their role in optimizing outcomes for AIS patients.

Conflict of Interest

The authors imply no conflict of interest.

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Abbreviation List

AIS: Adolescent idiopathic scoliosis
3D: Three-dimensional
UHSS: Ultrahigh strength stainless steel
CoCr: Cobalt-chromium
Ti: Titanium
MRI: Magnetic resonance imaging
PJK: Proximal junctional kyphosis
SMM: Shape-memory metal

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