Impact of Connector Placement and Design on Bending Stiffness of Spinal Constructs

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■ OBJECTIVE: **To evaluate the stability of multiple rod—connector construct designs using a mechanical 4-point bending testing frame.**

■ METHODS: **A mechanical study was used to evaluate the bending stiffness of 3 connectors across 12 different configurations of rod—connector—rod constructs. Stability was evaluated in flexion—extension and lateral bending. Combinations of rods having 1 of 3 diameters (4.0 mm, 5.5 mm, and 6.0 mm) connected by 1 of 3 connector types (parallel open, snap-on, and hinged) were compared. Configurations with single connectors and with double connectors with variable spacing were also compared to simulate revision surgery conditions.**

■ RESULTS: **Constructs consisting of 4.0-mm rods connected to 4.0-mm rods were significantly less stiff as the total number of connectors used in a series exceeded 2. When single-connector configurations were compared, parallel open rod connectors demonstrated greater stiffness in flexion—extension than hinged open connectors, whereas hinged open connectors demonstrated greater stiffness in lateral bending. Using double connectors increased stiffness of 4.0- to 4.0-mm rod configurations in flexion—extension and lateral bending, 4.0- to 6.0-mm rod configurations in flexion—extension, and 5.5- to 6.0-mm rod configurations in lateral bending. Spacing the double connectors significantly improved lateral bending stiffness of 4.0- to 4.0-mm and 5.5- to 6.0-mm rod configurations.**

■ CONCLUSIONS: **Our data indicate that the design, number, and placement of rod connectors have a significant impact on the bending stiffness of a surgical construct. Such mechanical data may influence construct design in primary and revision surgeries of the cervical spine and cervicothoracic junction.**

INTRODUCTION

Spinal instrumentation is a key component in the management of spinal pathology.[1-10] Most commonly, instrumentation used during posterior cervical stabilization involves bilaterally placed lateral mass screws spanned by longitudinal rods.[11,12] Rod placement must account for individual anatomy and the distinct pathology; in certain instances, this requires using 2 rods connected by rod-to-rod branch connectors to avoid unnecessary bending or to connect larger diameter rods to smaller diameter rods. In addition, the frequency of revision surgery is increasing after either biological or mechanical failure. Although this surgery is more common in the lumbar spine, the cervical spine—particularly in the setting of deformity correction—is subject to significant stressors and may require the use of multiple series of connectors with either extra rods for additional stability or appropriate reconstruction.

Despite the frequent use of connectors in cervical and lumbar surgery, there is a paucity of published data on the mechanical stability of different construct designs to guide surgeon decision-making. Several biomechanical studies have not observed differences in stability between 1 rod and 2 rods connected with a single connector; nonetheless, data are lacking regarding the influence of multiple connectors, connector design, and the use of multiple rod diameters on biomechanical stiffness during posterior spinal fixation.[1,13-16]

Four-point bending is a common and simple noncadaveric, mechanical method of testing material strength that has been used to evaluate spinal arthrodesis in animal models.[17] The method evaluates stresses during a known pure moment with

Key words
- Bending stiffness
- Biomechanics
- Cervical spine
- Component testing
- Instrumentation
- Spinal fixation implant

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*Citation: World Neurosurg. (2019) 121:e89-e95.
https://doi.org/10.1016/j.wneu.2018.08.235*

Journal homepage: www.journals.elsevier.com/world-neurosurgery

Available online: www.sciencedirect.com

uniform force in a nonfailure mode. This presents a controlled environment for evaluating the mechanical nuances of connector design and placement without the impact of stress-loading between cadaver and instrumentation. Although this may ignore essential elements of a spinal construct, such as screw–rod interface and multiple points of attachment, it facilitates a focused and systematic analysis of stability at high-stress attachment sites.

Understanding the impact of connector design and location on construct stiffness during spinal instrumentation is necessary for maximizing surgical success in primary and revision surgery. The goal of this study was to compare the construct stiffness of multiple rod–connector configurations using a nondestructive mechanical 4-point bending system. We hypothesized that configurations with larger connectors, spaced farther apart, and involving wider diameter rods would demonstrate greater bending stiffness.

METHODS

Testing Conditions

A total of 3 connector designs were studied (Figure 1) across 12 total conditions. Each connector design was evaluated in several configurations in its corresponding group (Figure 2) based on the number of connectors (1–4) used and the spacing between double connectors (close-spaced or far-spaced [20 mm apart]). The rod diameter for each group was based on the specifications of the connector that was used. Each configuration was tested in 2 positions simulating lateral bending and flexion–extension 3 times (Figure 3). Multiple configurations were evaluated; in several instances, the configurations were tested to the extreme (nonclinical scenario) in an attempt to identify trends in stability.

In group 1, a titanium parallel open-rod connector connecting two 4.0-mm rods (Cervifix System; DePuy Synthes Spine, Inc., Raynham, Massachusetts, USA) was evaluated in 6 configurations: 1) 2 overlapping rods, 1 connector; 2) 2 overlapping rods, double far-spaced connectors; 3) 2 overlapping rods, double close-spaced connectors; 4) 3 rods, 2 connectors; 5) 4 rods, 3 connectors; and 6) 5 rods, 4 connectors. In group 2, titanium parallel open rod connectors (Cervifix System; DePuy Synthes Spine, Inc.) connecting a 4.0-mm rod to a 6.0-mm rod were evaluated in 3 configurations: 1 connector, double far-spaced connectors, and double close-spaced connectors. In group 3, single-hinged connectors (titanium snap-on trans-connectors; Matrix Deformity System, DePuy Synthes Spine, Inc.) used to connect a 5.5-mm rod to a 6.0-mm rod were evaluated in 3 configurations: 1 connector, double far-spaced connectors, and double close-spaced connectors. Of note, the hinged connector is intended as a transverse connector between parallel rods. All rods and connectors were made from medical-grade nickel–titanium alloy.[18]

Mechanical Testing

In all conditions tested, constructs were studied using standard 4-point bending (per American Society for Testing and Materials F382 and F2193) on a custom-built test fixture (Figure 3) and a standard servohydraulic test system (MTS Systems Corp., Eden Prairie, Minnesota, USA). The advantage of 4-point bending is that the resulting pure-bending moment is uniform between the 2 inner loading pins. All rod configurations (Figure 2) were loaded in 2 different orthogonal planes to simulate bending during flexion–extension (frontal plane) and lateral bending (coronal plane). Each configuration was tested in flexion first (with set screws oriented posteriorly) followed by lateral bending (construct rotated 90°) (Figure 3). Flexion–extension and lateral bending were chosen as the imposed pure-bending moment, given the regular use as the direction for bending during cadaveric testing. Loading was applied at a rate of 10 mm/min to a maximum of 500 N with load and displacement recorded at 10 Hz.

Analysis

Stiffness for each case was determined from the slopes of the respective force-versus-displacement graphs. One-way analysis of variance was used to determine statistically significant differences among groups, and the Holm-Šídák method was used to determine statistical significance between individual configurations. The overall significance level was set at $P < 0.05$.

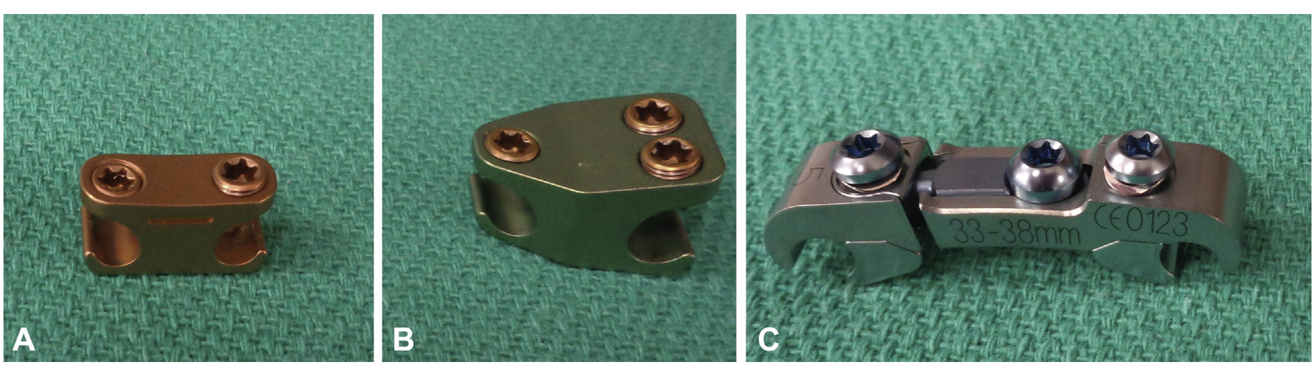

Figure 1. Connector types. (**A**) Titanium parallel open rod connector used to join a 4.0-mm rod to a 4.0-mm rod. (**B**) Titanium snap-on rod connector used to join a 4.0-mm rod to a 6.0-mm rod. (**C**) Titanium snap-on trans-connector used to join a 5.5-mm rod to a 6.0-mm rod. (Used with permission from Barrow Neurological Institute, Phoenix, Arizona, USA.)

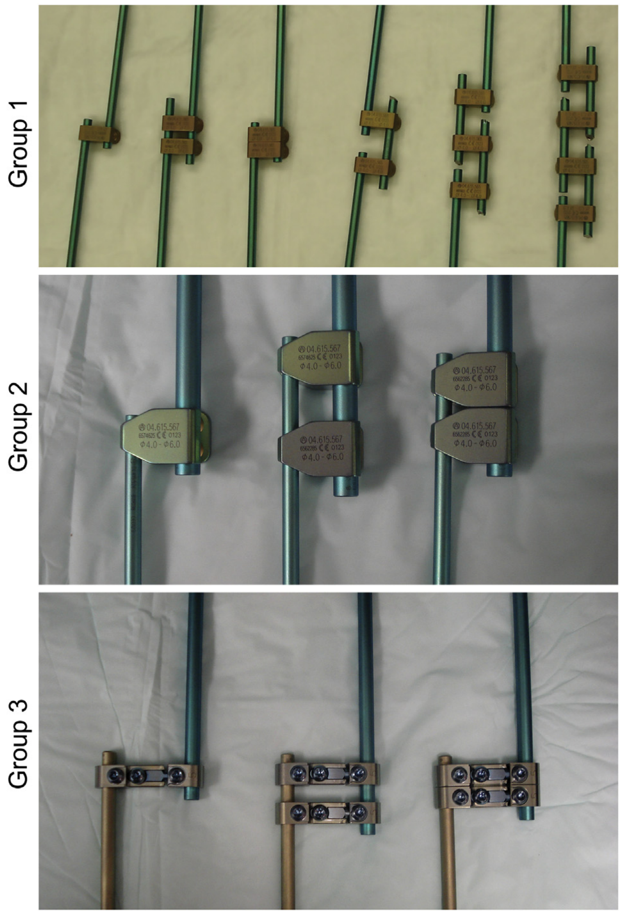

Figure 2. Rod testing configurations of all systems tested (listed from left to right in images). Group 1: 1) two 4.0-mm rods, 1 single connector; 2) two 4.0-mm rods, double connectors, spaced far ("double-spaced"); 3) two 4.0-mm rods, double connectors, spaced close ("double-close"); 4) three 4.0-mm rods, 2 single connectors; 5) four 4.0-mm rods, 3 single connectors; and 6) five 4.0-mm rods, 4 single connectors. Group 2: 7) 4.0- to 6.0-mm rods, 1 single connector; 8) 4.0- to 6.0-mm rods, double connectors, spaced far; and 9) 4.0- to 6.0-mm rods, double connectors, spaced close. Group 3: 10) 5.5- to 6.0-mm rods, 1 single connector; 11) 5.5- to 6.0-mm rods, double connectors, spaced far; and 12) 5.5- to 6.0-mm rods, double connectors, spaced close. (Used with permission from Barrow Neurological Institute, Phoenix, Arizona, USA.)

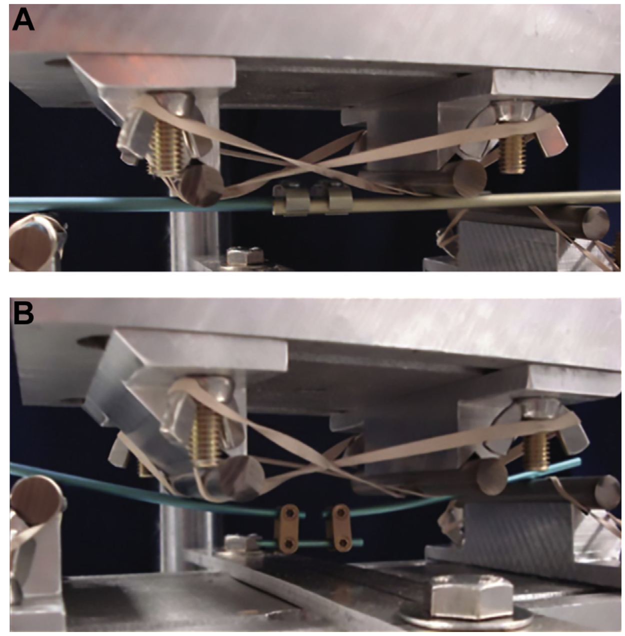

Figure 3. Standard 4-point bending (per American Society for Testing and Materials F382 and F2193) on a custom-built test fixture and a standard servohydraulic test system (MTS Systems Corp.). Each configuration is tested in (**A**) flexion—extension first (with set screws oriented posteriorly) followed by (**B**) lateral bending (construct rotated 90°). (Used with permission from Barrow Neurological Institute, Phoenix, Arizona, USA.)

RESULTS

Group 1: 4.0- to 4.0-mm Rod—Connector Configurations

All configurations using parallel open connectors between 4.0-mm and 4.0-mm rods were significantly stiffer during flexion—extension than during lateral bending ($P < 0.001$, Figure 4). During flexion—extension, with the configurations shown in Figure 2 (group 1), the mean stiffness decreased as the number of single connectors joining 4.0-mm rods in a series increased (Figure 4). The differences were statistically significant with 3 versus 1, 4 versus 1, and 2 versus 3 single connectors ($P \leq 0.02$) but not with 2 versus 1 or 4 versus 3 single connectors ($P \geq 0.53$). Doubling the

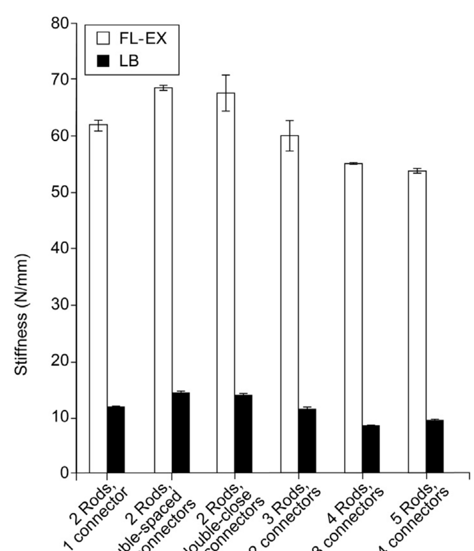

Figure 4. Stiffness of 4.0-mm rods connected with various connector configurations in flexion—extension (FL-EX) and lateral bending (LB). (Used with permission from Barrow Neurological Institute, Phoenix, Arizona, USA.)

connectors (configurations 2 and 3, Figure 2) resulted in significantly increased stiffness compared with that of a single connector (configuration 1, Figure 2) ($P \leq 0.008$), although spacing between double connectors had no effect ($P = 0.73$, Table 1).

The trend toward greater stability with double connectors was also observed during lateral bending tests of group 1. Double connectors (close and spaced) resulted in significantly increased stiffness compared with that of single connectors ($P < 0.001$); however, the far-spaced double connector construct was stiffer than the close-spaced double connector construct ($P = 0.04$, Table 1). Of the single connectors, 1 connector demonstrated greater stiffness than configurations with 2–4 single connectors ($P \leq 0.04$); 2 single connectors were significantly stiffer than 3 ($P < 0.001$) or 4 ($P < 0.001$); however, 4 single connectors demonstrated greater stiffness than 3 ($P < 0.001$) (Table 1).

Group 2: 4.0- to 6.0-mm Rod–Connector Configurations

Similar to the 4.0- to 4.0-mm configurations, configurations using open parallel connectors to join 4.0-mm rods to 6.0-mm rods were significantly stiffer during flexion–extension than during lateral bending ($P < 0.001$, Figure 5). During flexion–extension, the far-spaced double 4.0- to 6.0-mm connector configuration was significantly stiffer than a single 4.0- to 6.0-mm connector configuration ($P = 0.02$, Figure 5, Table 2); there was no significant difference between the close-spaced double connector and the single connector or between the far-spaced and close-spaced double connector configurations ($P \geq 0.05$). Although the mean stiffness during lateral bending was the greatest with far-spaced double connectors (Figure 5), the differences between configurations during lateral bending were not statistically significant ($P = 0.06$).

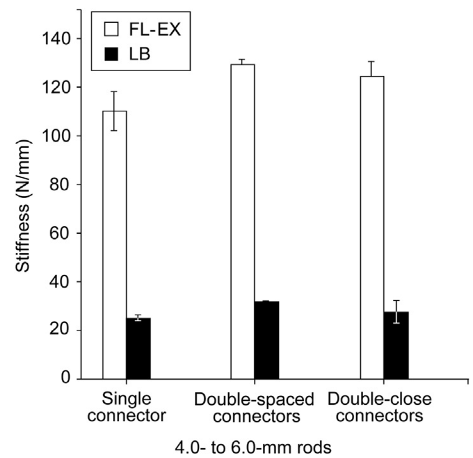

Figure 5. Stiffness of 4.0-mm rods connected to 6.0-mm rods with various connector configurations in flexion–extension (FL-EX) and lateral bending (LB). (Used with permission from Barrow Neurological Institute, Phoenix, Arizona, USA.)

Group 3: 5.5- to 6.0-mm Rod–Connector Configurations

Unlike the previously described connector configurations, the configurations using single-hinged connectors to connect 5.5-mm rods to 6.0–mm rods were significantly stiffer in lateral bending than flexion–extension ($P < 0.001$, Figure 6). No significant differences were observed between any of the 3 configurations during flexion–extension ($P = 0.34$) (Table 3, Figure 6). During lateral bending, the far-spaced double connector demonstrated significantly greater stiffness (59.2 N/mm) compared with the close-spaced double connector configuration (48.7 N/mm) ($P = 0.04$) and compared with the single-connector configuration (30.3 N/mm, $P = 0.007$). The close-spaced double connector configuration was stiffer during lateral bending than the single-connector configuration ($P < 0.001$) (Table 3, Figure 6).

Single-Connector Configurations

Of the single-connector configurations using differing diameter rods (4.0- to 4.0-mm, 4.0- to 6.0-mm, 5.5- to 6.0-mm), the 5.5- to 6.0-mm configuration was the least stiff during flexion–extension

Table 1. *P* Values for Intragroup Comparisons of Stiffness in Group 1 (4.0- to 4.0-mm Group)*

Connectors	Flexion–Extension	Lateral Bending
1 vs. 2 single	0.53	0.04
1 vs. 3	0.004	<0.001
1 vs. 4	0.001	<0.001
1 vs. 2 close	0.008	<0.001
1 vs. 2 spaced	0.006	<0.001
2 single vs. 3	0.02	<0.001
2 single vs. 4	0.005	<0.001
2 single vs. 2 close	0.002	<0.001
2 single vs. 2 spaced	0.001	<0.001
3 vs. 4	0.60	<0.001
3 vs. 2 close	<0.001	<0.001
3 vs. 2 spaced	<0.001	<0.001
4 vs. 2 close	<0.001	<0.001
4 vs. 2 spaced	<0.001	<0.001
2 close vs. 2 spaced	0.73	0.04

*By one-way analysis of variance.

Table 2. *P* Values for Intragroup Comparisons of Stiffness in Group 2 (4.0- to 6.0-mm Group)*

Connectors	Flexion–Extension	Lateral Bending
1 vs. 2 close	0.05	0.06
1 vs. 2 spaced	0.02	0.06
2 close vs. 2 spaced	0.35	0.06

*By one-way analysis of variance.

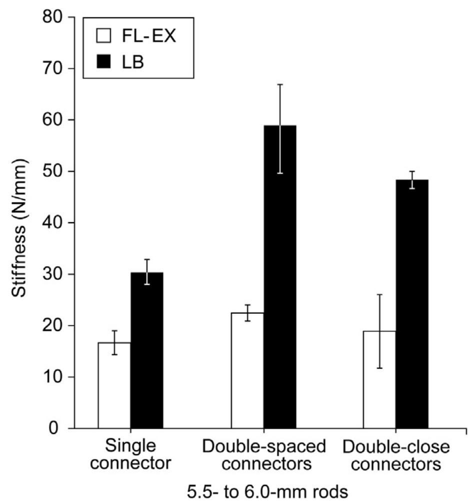

Figure 6. Stiffness of 5.5-mm rods connected to 6.0-mm rods with hinged connectors in flexion—extension (FL-EX) and lateral bending (LB). (Used with permission from Barrow Neurological Institute, Phoenix, Arizona, USA.)

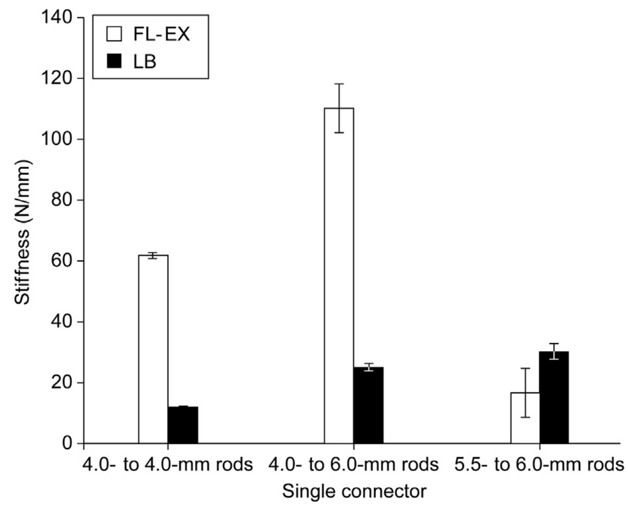

Figure 7. Comparison of 3 different-sized rod constructs each with a single connector (flexion—extension [FL-EX] and lateral bending [LB]). (Used with permission from Barrow Neurological Institute, Phoenix, Arizona, USA.)

($P < 0.001$) (**Figure 7**); the 4.0- to 4.0-mm configuration was less stiff than the 4.0- to 6.0-mm configuration ($P < 0.001$). During lateral bending, the 5.5- to 6.0-mm configuration demonstrated greater stiffness than both the 4.0- to 4.0-mm configuration ($P < 0.001$) and the 4.0- to 6.0-mm configuration ($P < 0.001$), and the 4.0- to 4.0-mm configuration was less stiff than the 4.0- to 6.0-mm configuration ($P = 0.008$) (**Table 4**).

DISCUSSION

Instrumented fixation using rods and screws is an essential component in the surgical management of spinal disorders. The magnitude of stiffness a construct can attain depends on many variables that are related to the biological properties of the tissue, the physical properties of the materials used, and the design of the construct. Historically, factors such as screw trajectory, rod material, and rod diameter have been investigated to optimize mechanical resistance to motion. More recently, given the increasing rate of deformity correction surgeries and of revision surgeries, interest in the impact of using multiple rods and connectors has grown. Whereas the impact of a single connector has been investigated previously, the degree to which multiple connections and different connector types influence stiffness remains unknown.

The current study used an established 4-point bending-test protocol to examine the effect on mechanical stiffness due to the number of connectors used, connector placement, and connector design (parallel open and single-hinged) in configurations with multiple parallel rods. The 4-point bending-test protocol was chosen to evaluate specific connector and construct design without the influence of stress-loading between cadaver and instrumentation. In some cases, nonclinical configurations were used in an attempt to identify trends in stability. We hypothesized that fewer connections, double connectors across overlapping rods, increased spacing between double connectors, and an increased connector cross-sectional area would lead to increased stiffness.

As expected, an increasing number of serial connections resulted in decreased overall construct stiffness in both planes of motion. Conversely, placing double connectors across overlapping

Table 3. *P* Values for Intragroup Comparisons of Stiffness in Group 3 (5.5- to 6.0-mm Group)*

Clamps	Flexion—Extension	Lateral Bending
1 vs. 2 close	0.34	<0.001
1 vs. 2 spaced	0.34	0.007
2 close vs. 2 spaced	0.34	0.04

*By one-way analysis of variance.

Table 4. *P* Values for Intragroup Comparisons of Stiffness of Single-Connector Constructs*

Type (Rods, Connector)	Flexion—Extension	Lateral Bending
4.0 to 4.0 mm, single vs. 4.0 to 6.0 mm, single	<0.001	0.008
4.0 to 4.0 mm, single vs. 5.5 to 6.0 mm, single	<0.001	<0.001
4.0 to 6.0 mm, single vs. 5.5 to 6.0 mm, single	<0.001	<0.001

*By one-way analysis of variance.

rods resulted in increased stiffness in a connector type—dependent manner, suggesting that specifics of either connector design or rod diameter differentially impact construct stiffness across the 2 planes. Because of the study design, we are limited in our ability to determine the relative contributions of rod diameter and connector design to overall stiffness. Of note, increased spacing (20 mm) of double connectors contributed to significantly increased stiffness in lateral bending in both parallel open and single-hinged connector types (group 1, group 3).

Previous biomechanical studies have not found significant differences between single rods and 2 rods attached by connectors. Eleraky et al.[16] described similar stiffness in flexion—extension and axial rotation between a single 3.5-mm rod, a tapered dual-diameter single rod, and a 2-rod (3.5- to 5.0-mm) construct attached with a "wedding band" connector. Although the current study did not investigate single continuous rods (no connectors), we did observe a trend of decreasing stiffness with an increase in the number of connectors, suggesting a limit to the number of connections that can be made in a series without significantly affecting construct stiffness. In a noncadaveric study of rod diameter and 2 connector types (solid vs. hinged domino connectors), Tatsumi et al.[1] demonstrated that solid connectors were better than hinged connectors in yield-fatigue testing. Although these authors found that in certain conditions larger diameter connected rods had greater stiffness than single rods, we found in our study that this trend was not maintained across multiple (>2) connections. Although a direct comparison of results is challenging because of variations in testing methodologies, both the current study and that of Tatsumi et al. indicate that connector type and rod diameter can influence mechanical performance of spine constructs.

Parallel open connectors are designed to connect branch points of rods, with a coronally oriented clasp opening that buttresses flexion—extension resistance. However, single-hinged transverse connectors are designed with a frontally oriented C-shaped opening; this design has been suggested by previous studies as the most effective in providing torsional rigidity.[19] In addition, authors have demonstrated the biomechanical benefit of using 2 transverse connectors between parallel bilateral rods for improved torsional resistance. Shaw et al.[19] observed improved resistance with 2 spaced connectors in lateral bending and axial rotation, and Kuklo et al.[20] found a 15% additional improvement in axial stability of 2 spaced connectors over a single connector in the thoracic spine. However, no previous studies have demonstrated the added stiffness gained in lateral bending by using spaced double connectors between parallel unilateral rods. As with transverse connectors, the improved resistance is likely due to force coupling across the overlapping segment, leading to a larger pure-bending moment being generated with increasing distance. This has strong implications for long-construct designs, particularly when considering placement of connectors across dual-diameter rods.

Limitations

Limitations of our study include the constraints of using a mechanical testing paradigm; such a model system can evaluate only the mechanical properties of rod—connector constructs and cannot easily be extrapolated to in vivo or in vitro cadaveric studies. In addition, because screw types were not evaluated in this study, the implant—bone interface was not addressed; this interface is well documented as a frequent site of clinical failures and may therefore detract from the clinical and in vivo applicability of the data. Our model also removes motion effects and the clinically important failure mode of fatigue loading between the multiple cervical points, given static displacement controlled testing; the custom testing machine we used also induces a cantilever-like bending effect, rather than the motion lever on the distal instrumentation that would be observed in a biomechanical testing paradigm with multiple attachment points. A failure mode testing paradigm would be of interest in the future, particularly to assess location of failure (between connectors or at the connector-rod interface). In addition, the testing paradigm did not include axial rotation, which is another important axis of strain in the cervical spine, nor was lateral bending measured on both open and closed side, limiting our ability to fully evaluate construct stiffness and connector design. The research design also is limited by the lack of a control group (i.e., a nonconnected rod group) to provide a reference value. Finally, our model carries an implicit assumption that increased implant stiffness and mechanical strength equate to greater clinical success.

Nevertheless, we do not believe that these methodologic design limitations detract from the practical application of the data. Mechanical testing models do have an advantage over clinical or cadaveric models because they exclude the significant amount of variability that exists among patients and cadaveric specimens. The 4-point bending test delivers a uniform single type of load, representing an effort to isolate the response of a connector under carefully controlled mechanical conditions without the influence of cadaveric load sharing. Therefore, despite these limitations, the current study provides valuable information about the mechanical performance of various rod—connector configurations to guide connector choice and construct design in an effort to maximize stiffness and minimize rotational motion. Future evaluations of such connectors using cyclic loading (noncadaveric) and cadaveric studies are warranted and would help validate mechanical stability and strain distribution.

CONCLUSIONS

Data from 4-point bending indicate that connector design (i.e., orientation of rod opening and cross-sectional area) plays an important role in the torsional resistance of cervical spine rod—connector constructs. Although construct stiffness is impacted negatively by increasing the number of connectors and connections, stiffness can be optimized by using 2 connectors (doubling) at the rod overlap attachment points and spacing these connectors farther apart.

ACKNOWLEDGMENTS

The authors graciously acknowledge DePuy Synthes Spine for the donation of instrumentation for this study.

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Received 31 May 2018; accepted 31 August 2018

Citation: World Neurosurg. (2019) 121:e89-e95.
https://doi.org/10.1016/j.wneu.2018.08.235

Journal homepage: ***www.journals.elsevier.com/world-neurosurgery***

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