ORIGINAL ARTICLE

Fatigue Testing of a Titanium Tapered Rod *versus* Two Rods Connected by a Parallel Connector across the Cervicothoracic Junction: A Biomechanical Study

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Abstract

This study compares the fatigue failure of a tapered titanium-rod construct against two connected titanium rods (domino construct) across the cervicothoracic junction. All testing was carried out in a simulated flexion-extension plane. The 3.5-mm/6.0-mm tapered titanium rod and the 3.5-mm titanium rod, connected to a 6.0-mm titanium rod with a connector, were compared for their fatigue failures. Six specimens of each construct were tested in a cantilever displacement control method using 6 different amplitudes. Each specimen was cycled to failure or to 2.5 million cycles (run out) at 10 Hz. Failure was defined as rod fracture. The domino construct reached the test limit of 2.5 million cycles at ± 0.45 mm (72 N) but failed in all the other tested amplitudes. The tapered rod construct reached the test run out limit of 2.5 million cycles at higher amplitudes than the domino construct at ± 0.9 mm and failed in all the other tested amplitudes. The study showed that the tapered-rod construct across the cervicothoracic junction is more fatigue resistant than the domino construct.

Keywords

Thoracic vertebrae; Spinal fusion; Materials testing; Torsion; Mechanical; Stress; Mechanical

Introduction

The cervicothoracic junction (CTJ) is a complex transitional zone, where the relatively mobile cervical spine articulates with the rigid thoracic spine[1]. Additionally, at the CTJ, the spine curvature shifts from being lordotic at the cervical spine to kyphotic at the thoracic spine. These factors subject the CTJ to unique biomechanical forces that are absent elsewhere in the spine[2]. The incidences of traumatic cervicothoracic injuries were reported to be 9% of all spinal injuries, including fractures, fracture-dislocations, facet dislocations, and subluxation[2]. Apart from traumatic injuries, the CTJ can be affected by a wide variety of pathologies, including inflammatory disorders, infections, primary and metastatic tumors, spondylosis, and congenital abnormalities[3]. All these factors can result to excess stress, being placed on the spine instrumentation across this junction[3].

Due to the biomechanical complexity of the cervicothoracic junction, several instrumentation types and surgical techniques had been described in literature, ranging from wiring to screw-rod systems[4]. One of the promising modalities is the dual diameter or tapered rod that allows a stable connection between the small cervical screws and the large thoracic screws, avoiding the need to place two separate constructs[5]. Another modality is the use of a parallel connector to connect two rods of different diameters across the CTJ[6]. Some biomechanical studies compared these different constructs on the CTJ in terms of stability, ROM, yield force, and stiffness[6-8]. However, there are no studies that compare fatigue failure of titanium dual diameter rod to titanium connected-rod constructs.

In this pilot biomechanical study, we sought to compare the fatigue failure of a 3.5/6.0 mm dual diameter titanium rod to 3.5 mm and 6.0 mm titanium connected rods (domino construct). We hypothesized that there is no difference in fatigue failure between a dual diameter titanium rod and the connected titanium rods.

Materials and Methods

Two constructs, SYNAPSE™ System (DePuy Synthes Co., Warsaw, IN, USA) were tested in a way that simulates a posterior spinal fusion between C6 and T1: the tapered titanium rod construct, 6.0 mm tapered to 3.5 mm, and the domino construct, 6 mm rod connected by a connector to 3.5 mm rod. The distance between the insertion point of the C6 lateral mass screw and insertion point of the T1 pedicle screw at the cervicothoracic junction was measured on ten CT scans using a general electric machine. The sequential axial CT images were obtained through the cervical spine without contrast. Additional high-resolution coronal and sagittal reconstructed images were also obtained for better visualization of the osseous structures. The average distance was 31 mm. Therefore, the construct was fixed at two points 31 mm apart. Specifically, the length of the 3.5 mm diameter rod was standardized at 11.5 mm for both constructs. One end was fixed to the XY base, and the other end was attached to a spherical bearing rod end, with the connector or the tapered part of the construct falling in the middle (Figures 1, 2, and 3). In this way, the fixed end was permitted to translate in the X and Y horizontal directions, and the displacement was applied in the Z vertical direction, while allowing the 3.5 mm rod to pivot and rotate within the spherical bearing. The test was done in the flexion-extension plane with the parallel connector "dominos", facing up and bending in the up and down (Z-axis) direction.

A preliminary test was done by displacing the domino construct by 3 mm at 0.1 mm/s, then returning to its original position at the same rate. The rod was deformed by 0.606 mm, when the load had returned to 0 N. The yield point started at around 170 N. This plastic deformation implies that the construct had failed. Based on this result, it was concluded that cyclic testing could be performed on the Instron ElectroPuls® E10000 (Instron Corp., Norwood, MA, USA), which is capable of cyclic loading of ±3 mm displacement at 10 Hz, with loads well above 170 N.

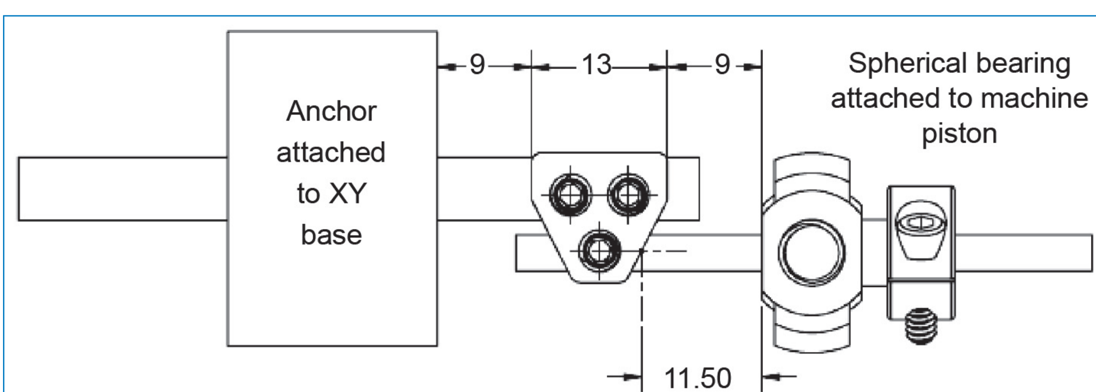

Figure 1. The domino connected rod construct (top view).

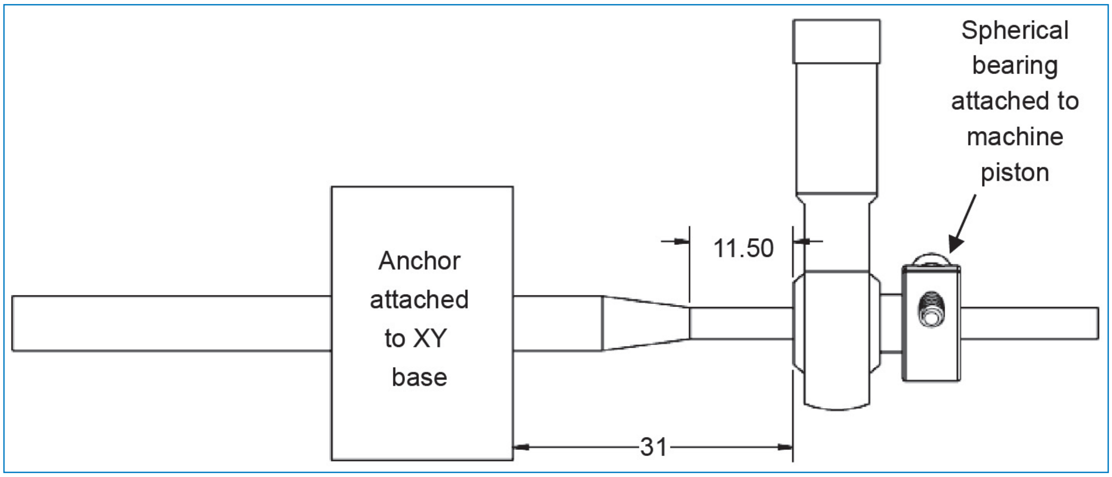

Figure 2. The tapered titanium rod construct (side view).

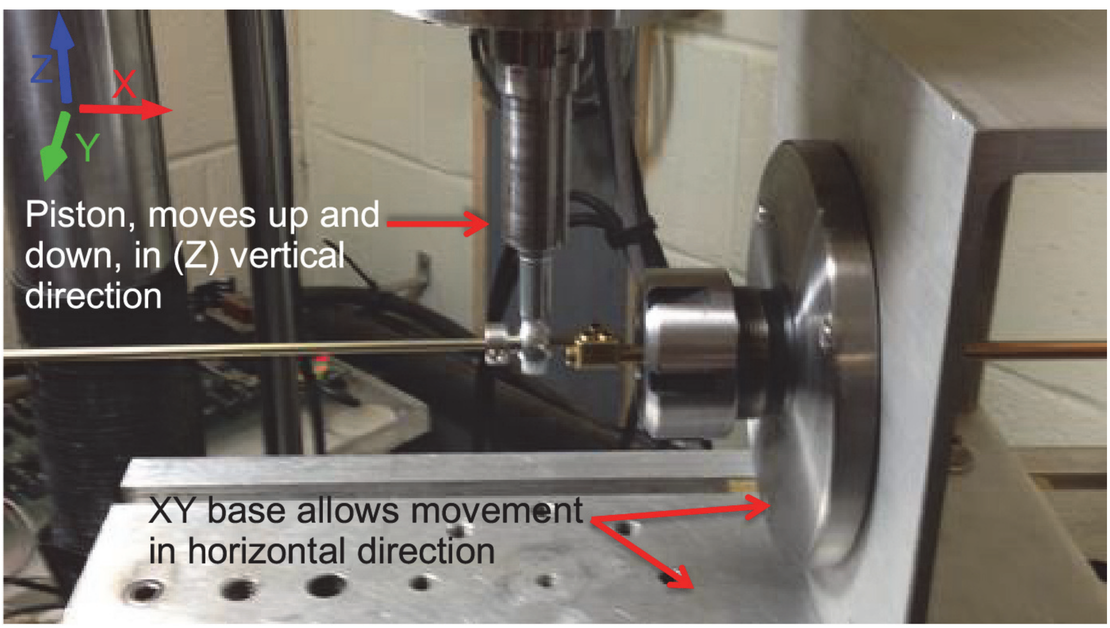

Figure 3. Tested construct assembled to the testing machine.

Six specimens of each construct were tested with the cantilever displacement control method using the ElectroPuls at 6 different amplitudes. The load (N) data were recorded at 100 Hz.

The domino construct was cycled at ±3 mm (230 N), ±2 mm (193 N), ±1.5 mm (149 N), ±0.75 mm (115 N), ±0.5 mm (80 N), and ±0.45 mm (72 N). The tapered construct was cycled at ±3 mm (350 N), ±2 mm (255 N), ±1.5 mm (160 N), ±1.25 mm (155 N), ±1.0 mm (145 N), and ±0.9 mm (130 N). Each specimen was cycled to failure or to 2.5 million cycles (run out) at 10 Hz. Failure was defined, when the rod fractured. Because the domino construct was failing at lower amplitudes, compared to the tapered one, we had to run it at amplitudes lower than the tapered rod to aim for the closest fatigue failure point. This was done for the last three amplitudes of the domino construct.

Results

The domino construct reached the test limit of 2.5 million cycles at ± 0.45 mm (72 N), while it failed in all other tested amplitudes. All failed rods for the domino construct broke at the junction between the connector and the 3.5 mm rods. The domino construct reached 323 cycles (230 N) at ± 3 mm, 2,200 cycles (193 N) at ± 2 mm, 4,725 cycles (149 N) at ± 1.5 mm, 27,270 cycles (115 N) at ± 0.75 mm, and 393,045 cycles (80 N) at ± 0.5 mm (Table 1). The tapered rod construct failed at 104 cycles (350 N) at ± 3 mm, 1,182 cycles (255 N) at ±2 mm, 9,016 cycles (160 N) at ± 1.5 mm, 19,227 cycles (155 N) at ± 1.25 mm, and 328,415 cycles (145 N) at ± 1.0. It reached the test run out limit of 2.5 million cycles at ± 0.9 mm (130 N) (Table 2). All failed rods for the tapered construct broke at the smaller end of the tapered area.

The load to number-of-cycles-at-failure curve shows that the tapered construct supported higher loads at failure, compared to the domino construct (Figure 4).

Discussion

Stabilization of the cervicothoracic junction is challenging, as it bears a large force secondary to the transition between the flexible cervical and rigid upper thoracic spine segments. Different constructs are available to stabilize the CTJ by utilizing either a constant-diameter rod across the cervicothoracic junction, tapered rod or two different diameter rods connected with a “domino". Clinically, fatigue failure (cyclic loading) is the most common mode of failure in spine implants[9]. Many studies had evaluated the biomechanical characteristics of cervicothoracic constructs, but none of them looked at the fatigue failure[6,7]. Our study looked at fatigue failure and showed that the domino construct was more susceptible to fatigue than the tapered rod construct.

Table 1. The domino connected rod construct (top view)

Amplitude (mm)	Average Load at End of Test (N)	Number of Cycles to Failure
3.0	230	323
2.0	193	2,200
1.5	149	4,725
0.75	115	27,270
0.5	80	393,045
0.45	72	Did not fail at 2.5 million

Table 2. Average load at failure (N) and number of cycles reached for tapered rod construct

Amplitude (mm)	Average Load at End of Test (N)	Number of Cycles to Failure
3.0	350	104
2.0	255	1,182
1.5	160	9,016
1.25	155	19,227
1.0	145	328,415
0.90	130	Did not fail at 2.5 million

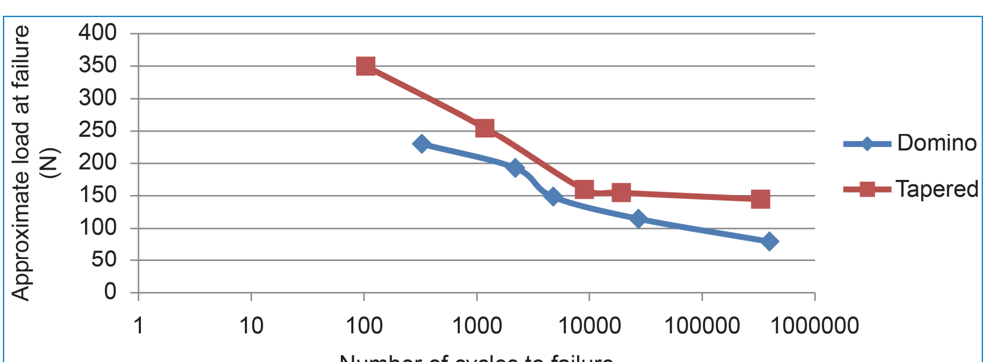

Figure 4. The load to number-of-cycles-at-failure curve.

On the other hand, Tatsumi *et al.*[6] did biomechanical testing using polyethylene blocks and reported that the two constructs showed similar stiffness and yield force. They also showed that the hinged domino construct, which we did not test, failed at the hinge axis, which was the weakest link in the construct. They concluded that the tapered rod and the solid domino-construct were not statistically distinguishable for any tested parameters in either flexion, bending, or axial rotation, suggesting that either construct should function similarly. These findings were also supported by Eleraky *et al.*[7], who did biomechanical testing of the tapered rod and the domino construct using cadaveric cervicothoracic junction vertebral bodies. They looked at flexion/extension/rotation and lateral bending stiffness for both constructs. Their results also showed that the tapered rod and domino construct appeared to share a similar stiffness. Those studies showed similar results, but our results also showed that there is a difference in fatigue failure between the two constructs. This difference is likely, because the rod taper relieves stresses better than the abrupt transition of the domino, permitting higher cyclic loads before failure. A single tapered rod sustained higher loads before failure compared to the domino construct. On the other hand, the domino construct failed at the junction of the domino and the 3.5 mm rod (rod-screw interface). Moving from the biomechanical perspective to the clinical significance, the mean annual cervical motion frequency at the cervical segment was 10.6 $\times 10^6$, 8.5 $\times 10^6$, and 5.6 $\times 10^6$ movements in flexion-extension, lateral bending, and axial rotation, respectively[10]. The high annual frequency of cervical motion highlights the importance of fatigue failure over one-time loading to failure. A recent clinical study demonstrated the efficacy of the tapered rod construct in a small case series[11]. None of these patients had any implant failure. The domino construct is an excellent option to join existing cervical or thoracic implants to new instrumentation at the other end of the spine, as it may save re-operation at the level of the existing instrumentation. As a disadvantage, the dominoes are bulky and require considerable manipulation, which could theoretically injure the exposed neural elements[11]. Furthermore, as these dominoes occupy space, bone graft placement may be compromised[11].

In such a situation, the tapered rod offers an excellent alternative method to connect the cervical and thoracic screws. They are less bulky and would allow easier bone grafting than the domino construct. There is a theoretical risk of the rod bending at the transition point but this has neither been reported in literature nor has been witnessed[11]. Despite the findings of this study, there are some limitations, including the use of a highly simplified model of spinal fusion in place of a fully instrumented spine. Each amplitude was run once, which made it difficult to obtain the mean and standard deviation. Failure at the bone-screw interface was not evaluated with this model, which is another limitation of this study. Furthermore, the effect of construct placement between the screws at C6 and T11, whether centered or offset cranially or caudally, was not investigated. It stands to reason that locating the domino block or the tapered portion of the tapered rod more cranially, closer to C6, would result in a shorter length of 3.5 mm rod, and therefore, a stiffer construct.

On the other hand, this is the only study that examines the fatigue behavior of different rod constructs. Future change in the design of the domino may improve the domino fatigue performance.

Conclusion

The tapered-rod construct was more fatigue resistant than the domino construct. This construct should be used, when linking 6.0 and 3.5 mm rods to avoid premature rod failures due to fatigue. Clinical studies comparing both constructs should be carried out to confirm the findings of this biomechanical study.

Conflict of Interest

The authors declares that they have no conflict of interest that is related to this study and this article.

Disclosure

The authors did not receive any type of commercial support either in the form of compensation or financial support for this case report. The authors have no financial interest in any of the products, devices, or drugs mentioned in this article.

Ethical Approval

The study was approved by the Ethics Committee of the KAUH in Jeddah, Kingdom of Saudi Arabia, also known as the Institutional Review Board of Hospitals.

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مقارنة الفشل بالجهد المتكرر لتركيبة قضيب التيتانيوم المدبب ضد تركيبة اثنين من قضبان التيتانيوم الموصولة (تصميم الدومينو) عبر منطقة التقاء فقرات العمود الفقري العنقي بالصدري: دراسة بيولوجية

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المستخلص. دراسة لمقارنة الفشل بالجهد المتكرر لتركيبة قضيب التيتانيوم المدبب ضد تركيبة اثنين من قضبان التيتانيوم الموصولة (تصميم الدومينو) عبر منطقة التقاء فقرات العمود الفقري العنقي بالصدري، تم تنفيذ جميع الاختبارات في مجال مشابه لحركة العنق العمودية، وتمت مقارنة قضبان التيتانيوم المتغير قطرها تدريجياً من ٣,٥ مم إلى ٦ مم وتصميم قضيب التيتانيوم مقاس ٣,٥ ملم المتصل بقضيب التيتانيوم مقاس ٦ مم بواسطة رابط الدومينو بإجراء اختبار الفشل بالجهد المتكرر، تم اختبار ست عينات من كل تصميم عن طريقة التحكم في الإزاحة العمودية من خلال ست قوى مختلفة وتم تدوير كل عينة للفشل أو إلى ٢,٥ مليون دورة عند تكرار ١٠ هرتز، و تم تعريف الفشل على أنه كسر القضيب، وصل تصميم الدومينو إلى حد اختبار ٢,٥ مليون دورة بمعدل +/- ٠,٤٥ مم (٧٢ نيوتن / ثانية) ولكنها فشلت في جميع الازاحات المختبرة الأخرى، ووصل تصميم القضيب المدبب إلى حد اختبار يصل إلى ٢,٥ مليون دورة بسعة أعلى من تصميم الدومينو، عند +/- ٠.٩ مم ، وفشل في جميع السعات المختبرة الأخرى، ولهذا فإن تصميم القضيب المدبب عبر منطقة التقاء فقرات العمود الفقري العنقية بالصدرية هوا أكثر مقاومة للفشل بالجهد المتكرر من تصميم الدومينو.