The influence of accessory rods and connectors on the dynamic response of spine fixation

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Abstract

Purpose This study presents a nondestructive technique to assess the influence of accessory rods and connectors on the dynamic response of spine fixation.

Methods Eighteen spine specimens were divided into three construct groups such as group I (2 rods [2R]), II (2 primary rods + 2 accessory rods with 2 transverse connectors [4R+2TC]) and III (2 primary rods + 2 accessory rods with 4 transverse connectors [4R+4TC]). Anterior corpectomy was performed for all specimens. A custom test setup was built to assess the dynamic responses of constructs in flexion-extension (FE) and left-right lateral bending (LRLB) motions. This setup can slide in lateral direction, and it is excited with an electrodynamic shaker vibrated at band limited random frequencies. Accelerometer and reusable dynamic strain sensors were installed on constructs to monitor the dynamic responses. Quasi-static eccentric loading tests were performed to determine the range of motion (RoM).

Results The results demonstrated that accessory rods significantly increase the resonance frequency (RF) and decrease the strain over standard 2R construction. Although 4R+4TC provided greatest reduction in rod strain over 4R+2TC and 2R, additional 2 connectors have no significant influence on dynamic response in FE motion.

Conclusions An increase in the number of rods has a significant role on the improvement of the fixation's integrity in FE and LRLB motions. However, the additional transverse connectors have significant involvements only in LRLB motion. RF obtained from dynamic tests correlated with the RoM which indicates that the technique could be used as an addendum to the quasi-static test.

1 Introduction

Mechanical function of the spine largely depends on biomechanical properties of various structures such as intervertebral disks, pedicles, facet joints and ligaments etc. Degeneration in these structures can affect the spine integrity which can cause it to become unstable [1-3]. Progresses in spinal implants have allowed surgeons to greatly address spinal deformities of increasing complexity [4-6]. Long-level instrumentation in spinal surgery is performed for degenerative, traumatic and adult deformity corrections. However, the complication percentages are high that are associated with the failure of instrumentation [7-10]. Therefore, spinal instrumentation presents a unique biomechanical and clinical challenge [1-2].

Pedicle subtraction osteotomy (PSO) or vertebral column resection is a prevailing method performed with posterior fixation surgery for sagittal correction using rods and pedicle screws [2,11]. A classical 2-rod (2R) configuration was the first strategy to stabilize PSO. [12-13]. Although some studies reported positive clinical outcomes of 2R instrumentation, significant risk of complication could occur. One of these complications is implant failure [1,10]. The complication related to instrumentation has been reported to be 31% [12]. It has also been indicated that the rod breakage in 2R configuration is 16% [14]. In order to reduce problems due to rod fracture, 3R [1,15] and 4R configuration [1,2,10,11,] have been introduced with

positive outcomes. It has been demonstrated in some clinical studies that 4R has superior mechanical strength over standard 2R configuration [16-17]. In addition, some *in-vitro* biomechanical studies also revealed that strains in multi-rods are lower once compared to 2R [1,2,11]. However, the accessory rods (ARs) and transverse connectors' (TCs) effects on dynamic response of spine fixation remains uncertain. In this work, we demonstrate a simple nondestructive vibration based methodology for the determination of surgical construct integrity as an addendum to the currently implemented quasi-static test. We also assess the influence of ARs and TCs on the dynamic response of the spine fixation and investigate correlations between dynamic and quasi-static test results. The dynamic properties of the surgical constructs such as resonance frequencies (RFs), damping ratios and strains were determined using *in-situ* nondestructive dynamic tests. The range of motion (RoM) was observed by quasi-static eccentric loading tests.

2 Materials And Methods

2.1 Specimen preparation

A total of 18 spines (thoracic and lumbar vertebrae) were obtained from sheep having reached full development of the skeleton. Exclusion criteria include spinal deformity and pathology that could influence the outcomes of the work. The posterior spinous, interspinous ligaments and facet joints were preserved in each specimen. The ribs were excised with a distance 2 cm distal to the to protect costovertebral joints. Anterior corpectomy was performed for each specimen, while their posterior wall was preserved. Surgical constructs were implemented with pedicle screws ($\varnothing = 4.5$ mm), titanium rods ($\varnothing = 5$ mm) and transverse connectors. Three surgical construct scenarios were considered as follows.

- Group I (2R): A simple 2-rod instrumentation.
- Group II (4R+2TC): 2 primary rods with the addition of 2 accessory rods and 2 transverse connectors.
- Group III (4R+4TC): 2 primary rods with the addition of 2 accessory rods and 4 transverse connectors.

Each surgical construct scenario includes 6 specimens, and each scenario was labeled with a group (Fig. 1). The rods were not subjected to the pre-contour processes since they could easily fit on the spine. They were cut at the distal end level of the vertebra involved in the instrumentation. Once the specimens were instrumented, distal and proximal vertebra located at free ends were mounted in polyester paste that mixed with catalyst (Dibenzoyl peroxide) for the experimental biomechanical investigation. Saline solution (0.9 % NaCl) was used through the tests to preserve the hyperelastic and viscoelastic features of the specimens.

2.2 Nondestructive dynamic test setup

An experimental dynamic test setup was designed and built to identify the dynamic characteristics of the constructs (Fig. 2). This setup has a length of 750 mm, width of 350 mm and height of 350 mm. The base plate of the setup was mounted on two circular steel rails ($\varnothing = 25$ mm) having a length of 400 mm. The connections between base plate, rails and upper plate were performed by bolts. In order to fix the specimen on the plate, a custom 3D printed apparatus (fully dense) with a diameter of 160 mm and height of 75 mm was manufactured.

The constructed specimen which was located on plate was excited by a YMC/MS/50 type electrodynamic shaker. To include uncertainties and variability due to posterior spinous, interspinous ligaments and facet joints during vibration, the specimen was excited with band limited random frequencies at 0-350 Hz. The excitation level of the amplifier was set to be 3.4 V RMS (root mean square error). A spring was placed between the lower surface of the plate and base plate to prevent the system from moving away during excitation. The stretch magnitude of this spring could be controlled with a bakelite screw. This spring also prevents the impact effects between stinger and base plate during vibration at random frequencies. To measure the dynamic excitation load, an IEPE based dynamic force sensor (YMC) with a sensitivity of 9.39 mV/N was attached to the output of the shaker. In addition, an IEPE based accelerometer (YMC) with a sensitivity of 9.39 mV/g was attached to the proximal free end of the specimen. Furthermore, a reusable ICP piezoelectric strain sensor (PCB Piezotronics) has a sensitivity of 55.9 mV/ $\mu\epsilon$ was mounted to the middle edge of the primary rod with an adhesive that was recommended by the manufacturer of the sensor. The shaker was centered at the edge of the plate. The instrumented specimen and sensors were placed on the same axis line of the base plate's axis to reduce the torsional effects during excitation. The base plate slid on rails and the entire system was placed on a foam to minimize external sources of unmeasured excitation.

In brief, the procedures that implemented are as follows:

- a. The specimen was installed on a fixation apparatus that was located on a plate.
- b. Band limited random digital signals were created using MATLAB.
- c. The digital signals were converted to analog signals by transferring them to Agilent 33210-A type signal generator over TCP/IP network protocol.
- d. The analog signals were amplified using a YMC/LA/100 type amplifier.
- e. The amplified band limited signals were transferred to the shaker to excite the sample.
- f. The force sensor at base floor, accelerometer and dynamic strain sensor were connected to NI 9234 device.
- g. Once the setup was arranged, the tests were initiated. Totally, 8298 data points were acquired with a sampling rate of 1765.53 Hz for each test.
- h. The collected measurements were processed with Labview software and stored as raw data. Then, dynamics characteristics of the instrumented specimens were estimated using these data.

Each group includes 6 samples. The tests for each group's specimen were performed for two motion cases. In the first case, the measurements were obtained for FE, while in the second case they were collected for LRLB motion. The sensor measurements for each specimen were collected for six duplicated tests, and totally 72 datasets (each motion includes 36 sets) were acquired in each group. Each of this dataset consisted of 4 dimensions where the 1st is the time (s), 2nd is force (N), 3rd is acceleration (N) and 5th is the strain ($\mu\epsilon$).

2.3 Statistical analysis

Statistical comparisons between groups were performed using one-way analysis of variance (ANOVA) to determine the similarity and difference in resonance frequencies, damping ratios and absolute maximum strains. Mean values were shown with standard deviation. Differences between groups were significant at $p < 0.05$. In addition, Pearson's test was applied to determine the correlations between data with a confidence interval of 95%. The statistical analyses were implemented using SPSS 22.

3 Results

The excitation force measurements as well as their Welch power spectral density are represented in Fig. 3. It can be seen that the frequencies between 0 and 350 Hz are dominant. The raw measurements such as strains ($\mu\epsilon$) and accelerations (g) for a typical dataset are shown in Fig. 4. The magnitude of these measurements both for FE and LRLB in group I are higher than other groups. In addition, strain magnitudes measured in 4R+4TC group for FE were among the lowest between groups. However, to investigate whether the intensity is critical or not, statistical tests were performed as described in the following section. Fig. 5 shows the frequency response functions (FRF) for the excitation loads and acceleration responses. The uncertainties and variability in these specimens are high due to nonlinearities in hard-soft tissue of the spine. The peak resonance frequencies and damping ratios over the frequencies range were estimated using "modalfrf" and "modalfit" functions in MATLAB.

3.1 Statistical results of the resonance frequencies, damping ratios and absolute maximum strains

The statistical data for the three groups are summarized in Fig. 6 and Table 1. The statistical analysis demonstrated that the most significant differences concern resonance frequencies (RFs) and absolute maximum strains (AMS) ($p < .05$). For the FE motion, damping ratios at mod II are not different between groups ($F = .112$, $p = .894$). For the LRLB motion, there are also no significant differences between the groups' parameters such as 1st ($F = .441$, $p = .644$) and 2nd damping ratio ($F = 1.029$, $p = .361$).

Post-Hoc multi Tukey test was performed for multi comparison of groups. The details of the statistical analysis are given in Table 2-3. The results showed that RFs in the 2nd and 3rd groups are significantly higher than in the 1st group both for FE and LRLB motions. ($p < .05$). Compared with the 2R specimen, 4R+2TC and 4R+4TC constructs significantly increased the 1st RF in FE (17% and 18% improvement, respectively; both $p < .05$) and LRLB motion (11% and 24% improvement, respectively; both $p < .05$). In

addition, 4R+2TC and 4R+4TC constructs significantly reduced AMS compared with 2R configuration for FE (80% and 92% reduction, respectively; both $p < .05$) and LRLB motion (77% and 85% reduction, respectively; both $p < .05$). Although the average 1st RF for FE motion in 4R+4TC construct is higher than 4R+2TC, there is no significant difference between them ($p > .05$). Furthermore, while the AMS in the 4R+4TC construct group is lower than in the 4R+2TC group, no significant differences were observed. These results suggest that the additional ARs involve a significant effect on dynamic response of the constructed spine compared with the standard 2R configuration. In addition, while the additional TCs improve the 1st RF in LRLB, they have not a similar significant involvement in FE motion.

The RFs and AMS were also evaluated using receiving operating characteristics (ROC) analysis to identify how well the ARs and TCs influence the dynamic stability of the instrumented spine. The ROC curves are typically established by plotting true positive rate (TPR) against false positive rate (FPR) at various thresholds. A curve close to the TPR axis, the classification score rises, while it is close to the FPR axis the score declines. Therefore, the best possible classification is yielded at a point of (0,1). The performance of the curve is assessed via area under curve (AUC). The best performance is observed for AUC = 1, and the worst is for AUC = 0.5. Generally, an AUC of 0.5 is considered "no separation" between groups, 0.6 to 0.7 is "sufficient", 0.7 to 0.8 is "acceptable", 0.8 to 0.9 is "very good", and higher than 0.9 is "outstanding". Considering the first RF value (in FE motion) between 2R and 4R+2TC construct groups, the AUC value is 0.86 (Fig. 7). This result shows that the 1st RF in group I and II are separated with a score of "very good". However, once evaluating the 1st RF for the 4R+2TC and 4R+4TC groups in FE motion, the AUC is 0.58. This result indicates that the 1st RF values in group II and III could not be separated. The ROC results for the rest parameters are represented in Fig. 7. The overall ROC curves showed that the dynamic characteristic parameters are discriminated in group I vs. II, and group I vs. III constructs, while they are not discriminated in group II vs. III in FE motion. However, group III data are separated both from group I and II in LRLB, which shows that the additional transverse connectors influence the dynamic integrity of the constructed spine in lateral bending.

3.2 Correlation between the parameters of nondestructive dynamic and quasi-static eccentric loading tests

To determine the correlation level between dynamic and quasi-static characteristic data, we utilized eccentric loading tests for constructed spines that were investigated with nondestructive dynamic test setup. The quasi-static eccentric loading test was performed with a machine (Autograph/Shimadzu, Japan) at a low loading speed of 1.66 mm/s. First, the constructed specimen that its lower part was installed in polyester paste was fixed. Then, a compression force acted at a distance of 48 mm from the principal centroidal axis. The sample was equipped with an orientation sensor (BN0055, Bosch, Sensortec, Germany) to monitor the RoM. The construct was loaded quasi statically, and the data were acquired until the bending moment reached 7.5 Nm with a sampling rate of 20 Hz. [1,18].

Regression analysis showed that a linear dependence exists between the parameters of dynamic and quasi-static test results (Fig. 8). Positive significant correlation is observed between AMS and RoM in FE

($R = 0.749$, $p = 0.00$, "strong") and LRLB ($R = 0.691$, $p = 0.001$, "strong"). In addition, the 1st RF correlated negatively with RoM in FE ($R = -0.606$, $p = 0.008$, "strong") and LRLB ($R = -0.622$, $p = 0.006$, "strong") directions. The results confirm that a decrease in longitudinal rod strain or an increase in the resonance frequency is associated with a rise in structural integrity of the spinal construction.

4 Discussion

Degeneration in the spine's structures can affect the stability [1-3, 19-20]. The longitudinal rods used in fixation should preserve the structural integrity of the spinal construct. However these rods may fracture due to high stresses created in spinal fusion and fatigue. A wide variety of approaches have been suggested to reduce these stresses at high-risk regions including the use of anterior column and accessory rods [1,2,11]. The majority of studies investigating the structural integrity of the spinal construction have been mainly performed using the quasi-static test. This test is suitable in determining the RoM. However, the magnitude of bending moment to be implemented is not certain due to the uncertainties and variations in the spine's mechanical properties and anatomical shape. In some cases, the constructed spine may damage before the implemented load reaches a set value. Hence, this test can be destructive. In this study, we proposed an easy, and effective structural vibration based monitoring technique for the identification of the constructed spine's integrity. The most attractive feature of this method is that it is nondestructive and the physiological loads such as compression load and bending moment are not required to be implemented. This method is widely used in engineering applications to identify their structural health conditions. It is based upon the changes in stiffness that alter the response of the structure [21]. The technique has been applied in some biomechanical studies to determine structural alterations in soft/hard tissue [22-23].

In this study, we assessed the influence of ARs and TCs on the dynamic response of the spine fixation. To minimize the uncertainties, all samples were obtained from sheep that reached the full development of the skeleton. The first results showed that the specimens in group II and III have significantly higher RFs and lower AMS than group I specimens. These results demonstrated that ARs have comparable effect in increasing spine stability both for FE and LRLB motions. We compared these outcomes with some previous studies. Note that, comparison of previous works that investigate the influence of ARs on the spinal fixation is not easy due there is not a standardized *in-vitro* test protocol. However several clinical and cadaveric biomechanical studies performed using quasi-static tests documented similar findings. For instance, spinal constructs with 4-rods were observed to have lower rod strain, RoM and higher fatigue failure resistance compared with 2-rod constructs [1,2,11,17]. In addition, it has been reported in a retrospective study that rod fractures in 2-rod constructs are significantly higher than multi rod constructs [14]. A study concluded that revision surgery requirements are higher in 2-rod constructs than 4-rod constructs [24]. The addition of ARs offered some biomechanical advantages compared with the standard 2-rod configuration [1,2,11,16,17]. Our results showed that the 1st RF in 4-rod construct with two TCs increased significantly once compared with 2-rod construct both for FE (+17%) and LRLB (+11%) movements. We also found that the AMS was significantly reduced in multi rod constructs compared with standard 2-rod options both in FE (-80%) and LRLB (-77%) motions. A study performed flexibility test

on the PSO model reported that the strain in multi rod construction normalized to 2-rod configuration dropped to 74.7% in FE and 63.5% in LRLB [1]. In another study it was reported that primary rod strain was declined in 4-rod construct (77% reduction) compared with 2-rod construct [11]. These studies implemented conventional strain rosettes based on strain gage technology. Their configuration is known as a Wheatstone bridge circuit, and becomes non-linear above the upper and lower limits of range. The environmental temperature variations can also affect the measurements. Therefore, the measurement error occurred by using the rosettes is not clear.

As the second result, it was found that the addition of two TCs did not generate a significant decrease in AMS both for FE and LRLB motions. The addition of TCs also did not improve the 1st RF in FE motion. These results are in line with some data reported in literature. A study determining the RoM of the constructed thoracic spine with and without TCs reported that TCs did not influence the construct's in FE and LRLB stability [25]. It has also stated that the additional TCs did not decrease the RoM in both motions [26]. However we observed that the additional two TCs in group III constructs significantly increased the RFs with a small percentage in LRLB compared with group II constructs. The average improvements for the 1st, 2nd and 3rd RF are 1.42%, 1.15% and 3.50%, respectively.

While extensive studies documented the influences of multi rods on the kinematic of constructed spines, no experimental approaches addressing the dependence between quasi-static and dynamic test results of the constructs. In this study, AMS that were observed with dynamic tests positively correlated with RoM that were observed with quasi-static eccentric loading tests. In addition, RF and RoM were inversely proportional.

Although the presented *in-vitro* work successfully quantified the influence of ARs and TCs on the dynamic response of spine fixation using vibration based monitoring techniques, this study is not without limitations. First, the number of samples is essential for the determination of biomechanical response of each construct group. Hence, more specimens should be used. Second, the specimens were obtained from sheep due to limitation of human cadavers. Hence, these specimens may not reflect the human anatomic spine. Finally, the obtained measurements show only postoperative situations, and do not include biomechanical properties of spinal fusion. To determine the effects of ARs and TCs on biomechanical features of spinal fixation, a non-invasive vibration based technique can be deployed for *in-vivo* conditions.

In conclusion, this study presents a meaningful nondestructive methodology to assess the constructs' dynamic stability. An increase in the number of rods play a significant role in the improvement of the fixation integrity in FE and LRLB motions. However, the additional transverse connectors have significant involvements only in LRLB motion. Determining the construct's stability may allow us to predict the failure.

Declarations

Conflict of interest

The authors declare no competing interests.

Abbreviations

2R	A simple 2-rod instrumentation.
4R+2TC	2 primary rods with the addition of 2 accessory rods and 2 transverse connectors.
4R+4TC	2 primary rods with the addition of 2 accessory rods and 4 transverse connectors.
AMS	Absolute maximum strains
ARs	Accessory rods
AUC	Area under curve
FE	Flexion-extension
FPR	False positive rate
FRF	Frequency response function
LRLB	Left-right lateral bending
PSO	Pedicle subtraction osteotomy
RF	Resonance frequency
RFs	Resonance frequencies
ROC	Receiving operating characteristics
RoM	Range of motion
TC	Transverse connector
TCs	Transverse connectors
TPR	True positive rate

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Tables

Table 1 Dynamic test measurements' results						
	Characteristic	Group I (n=160)	Group II (n=160)	Group III (n=160)	F	p- Values
Flexion- extension	Frequency at Mod I (Hz)	117.24±14.11	136.68±12.83	138.63±23.34	16.622	.000*
	Frequency at Mod II (Hz)	176.10±11.24	185.92±10.22	188.06±15.68	9.202	.000*
	Frequency at Mod III (Hz)	215.13±25.94	233.51±19.58	241.68±44.16	6.641	.002*
	Damping ratio at Mod I	0.0563±0.0273	.0692±.0286	.1047+.0623	12.481	.000*
	Damping ratio at Mod II	0.0677±0.0189	.0651±.0328	.0682±.0370	.112	.894
	Damping ratio at Mod III	0.0743±0.0424	.1024±.0573	.0768±.0267	4.495	.013*
	Maximum strain (µε)	0.6445±0.5223	.1312±.1168	.0528±.0212	38.885	.000*
Left-right lateral bending	Frequency at Mod I (Hz)	124.50±12.93	137.67±18.89	153.84±16.26	29.548	.000*
	Frequency at Mod II (Hz)	170.46±18.97	177.21±25.88	191.10±16.91	9.090	.000*
	Frequency at Mod III (Hz)	227.9±24.02	240.85±41.18	280.94±45.66	18.946	.000*
	Damping ratio at Mod I	.0903±.1135	.1138±.1590	.1195±.1449	.441	.644
	Damping ratio at Mod II	.0965±.0683	.1398±.1975	.1070±.0992	1.029	.361
	Damping ratio at Mod III	.1638±.2162	.06916±.0264	.1503±.1729	3.658	.029*
	Maximum strain (µε)	.2027±.2196	.0468±.02754	.0305±.0122	19.871	.000*
* denotes the mean difference is significant at the 0.05 level and n represents the number of measurements for each group. Data are presented as mean ± standard deviation.						

Table 2 Multiple comparisons of biomechanical vibration parameters for flexion-extension motion using Post Hoc Tukey's test

Dependent Variable	(I) Group	(J) Group	Mean Difference (I-J)	Std. Error	p	95% Confidence Interval	
						Lower Bound	Upper Bound
Frequency at Mod I (Hz)	I	II	-19.4456*	4.1029	.000	-29.1999	-9.6912
		III	-21.3894*		.000	-31.1438	-11.6351
	II	I	19.4456*		.000	9.6912	29.1999
		III	-1.9438		.884	-11.6982	7.8104
	III	I	21.3894*		.000	11.6351	31.1438
		II	1.94388		.884	-7.8104	11.6982
Frequency at Mod II (Hz)	I	II	-9.8133*	2.9716	.004	-16.8782	-2.7484
		III	-11.9538*		.000	-19.0187	-4.8889
	II	I	9.8133*		.004	2.7484	16.8782
		III	-2.1405		.752	-9.2054	4.9243
	III	I	11.9538*		.000	4.8889	19.0187
		II	2.1405		.752	-4.9243	9.2054
Frequency at Mod III (Hz)	I	II	-18.3806*	7.4622	.040	-36.1216	-0.6398
		III	-26.5480*		.002	-44.2889	-8.8071
	II	I	18.3806*		.040	0.6398	36.1216
		III	-8.1673		.520	-25.9083	9.5735
	III	I	26.5480*		.002	8.8071	44.2889
		II	8.1673		.520	-9.5735	25.9083
Maximum strain ($\mu\epsilon$)	I	II	.5133*	.07289	.000	0.3401	0.6866
		III	.5917*		.000	0.4184	0.7650
	II	I	-.5133*		.000	-0.6866	-0.3401
		III	.07838		.531	-0.0949	0.2517
	III	I	-.5917*		.000	-0.7650	-0.4184
		II	-.07838		.531	-0.2517	0.0949

*The mean difference is significant at the 0.05 level.

Table 3 Multiple comparisons of biomechanical vibration test parameters in left-right lateral bending motion using Post Hoc Tukey's test

Dependent Variable	(I) Group	(J) Group	Mean Difference (I-J)	Std. Error	p	95% Confidence Interval	
						Lower Bound	Upper Bound
Frequency at Mod I (Hz)	I	II	-13.1656*	3.8226	.002	-22.2534	-4.0779
		III	-29.3344*		.000	-38.4222	-20.2467
	II	I	13.1656*		.002	4.0779	22.2534
		III	-16.1688*		.000	-25.2565	-7.0810
	III	I	29.3344*		.000	20.2467	38.4222
		II	16.1688*		.000	7.0810	25.2565
Frequency at Mod II (Hz)	I	II	-6.7459	4.9372	.362	-18.4836	4.9918
		III	-20.6428*		.000	-32.3806	-8.9051
	II	I	6.7459		.362	-4.9918	18.4836
		III	-13.8969*		.016	-25.6346	-2.1592
	III	I	20.6428*		.000	8.9051	32.3806
		II	13.8969*		.016	2.1592	25.6346
Frequency at Mod III (Hz)	I	II	-12.9510	8.9843	.323	-34.3103	8.4082
		III	-53.03896*		.000	-74.3982	-31.6797
	II	I	12.95105		.323	-8.4082	34.3103
		III	-40.08791*		.000	-61.4471	-18.7286
	III	I	53.0389*		.000	31.6797	74.3982
		II	40.0879*		.000	18.7286	61.4471
Maximum strain ($\mu\epsilon$)	I	II	.1558*	0.0302	.000	.0842	.2276
		III	.1722*		.000	.1006	.2440
	II	I	-.1558*		.000	-.2276	-.0842
		III	0.0164		.850	-.0553	.0881
	III	I	-.1722*		.000	-.2440	-.1006
		II	-0.0164		.850	-.0881	.0553

*The mean difference is significant at the 0.05 level.

Figures

Figure 1

Representative views of the constructs. a 2R: A simple 2-rod instrumentation. b 4R+2TC: 2 primary rods with the addition of 2 accessory rods and 2 transverse connectors. c 4R+4TC: 2 primary rods

configuration with the addition of 2 accessory rods and 4 transverse connectors. d Anterior corpectomy

Figure 2

Nondestructive experimental dynamic test setup for the determination of dynamic characteristic parameters. a Test setup. b A typical construct.

Figure 3

Excitation force sensor data. a Raw measurements. b Welch power spectral density

Figure 4

Typical raw data measurements for the three groups

Figure 5

Typical frequency response functions. a Flexion-extension. b Left-right lateral bending

Figure 6

Dynamic test results. (Whiskers represent the standard errors.)

Figure 7

ROC curves for the three construct groups' parameters. (The black points represent the optimum critical points of the curves.)

Figure 8

Correlation among parameters of nondestructive dynamic and quasi-static eccentric loading tests