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Appendix

A1. Identification of the segment's center of force balance (CFB): Spinal motion is constrained by the interplay between the intervertebral discs, the spinal ligaments, and the facet joints, yielding a kinematic response unique to the segment tested [(46)]. The segment's CFB constitutes the reaction center about which spinal muscles exert their moment in response to moment-based loading (flexion, extension, and torsion). To minimize the occurrence of unaccounted forces and moments, we elected to apply the kinematic test compressive load at the segment's CFB. Each segment was secured to a compression test device (Figure 2) such that the segments mid-sagittal and mid-coronal axes were aligned with the devices X and Y axes as indicated by lines inscribed on the aluminum rings. Using Indelible ink, we transferred these lines marking to the segment's top and bottom PMMA embedding for co-registering the segment's mid-sagittal and mid-coronal axes with the mechanical testing systems X and Y axes at the different stages of the test (Figure 2).
Using the mechanical X-Y table [0-25mm range, 0.01mm accuracy for both axes)], we first aligned the position of the intersection for the segment's mid-sagittal and mid-coronal axes with that of the line of force applied by the hydraulic test system (DDC 4000, Interlaken, MN). The segment was exposed to 10 compressive load cycles (25 – 250 N, 1Hz) to re-condition the discs with the arrangement of the needle bearing and steel plate, allowing the segment to freely deform along the sagittal plane under the applied compression loading. The compressive load was increased to100N and the X-Y table used to adjust the position of the spine with respect to the line of applied loading until the values for the sagittal (flexion-extension) and lateral (bending) moments, measured via a 6DOF load cell ((# 2), MC5-5000, AMTI, MA), were at a minimum. This location of the segment' CFB, projected to the segment's sagittal and coronal planes,
respect to the was marked on the PMMA mantles using indelible ink. These markings for the CFB were used for positioning of the compressive load application (follower load) for the kinematics tests and for the compressive test to measure the segment's compressive strength.

A2. Spinal kinematics testing device: The follower load (FL) method [(47)], widely accepted for the assessment of spinal kinematics *in-vitro*. The method requires either an external frame [(47)] or wire guides implanted in the vertebral body [(48)], to guide the application of compressive load. However, the introduction of critical osteolytic defects to simulate the disruption of the segment's anterior and middle columns significantly alters both the anatomy and structural integrity of the segment's vertebrae. Implanting either external frame or wire guides will likely alter the structural response of the lesioned segments and may risk the segment's premature failure. To allow the application of FL, we designed a specialized six-degrees-of-freedom (6DOF) spine testing device (Figure 3).
i. Specimen assembly: With the segment middle vertebra instrumented with the optical markers, the segment was registered to the device's superior and inferior aluminum rings (part # 1) such that the its midsagittal and mid-coronal axes were aligned with the devices X and Y axes. The superior ring (# 1) is secured via an indeterminate frame to a 6DOF load cell (# 13, MC3-1000, AMTI,

MA) to allow measurement of the segment's force and moment response. In turn, the 6DOF load cell is secured to a 3DOF passive kinematic arrangement, composed of a linear bearing (#14), allowing free rotation about the X-axis and free translation about the Y-axis, and a linear slide (# 15), allowing free translation about the X-axis. The linear slide (# 14) is mounted to the device's rigid frame (not shown for clarity). Please note that this arrangement resulted in the assembly ability to self-align with the line of force as applied by the load cables, thus preventing force imbalance developing due to the action of the loading systems on opposite sides of the main assembly (required for application of pure moments).

ii. Follower-load system: The force generated by the calibrated weights on both sides of the device, (#2) is transferred via a braided cable and two pullies (#3 and #4) to a ball-ended cable anchor (#5b). This anchor is attached via a frame (#5c) to the lower PMMA ring, thus completing the axial compression load system. An arrangement of two pin-in-slot joints (#6), allowed the linkage joint to follow the curvature of the deforming segments freely, guiding the braided cable to achieve a follower load type loading. Both the compression guide pully (# 4) and the cable anchor (#5b) were mounted via an ACME screw joint (# 5d) within the loading frames (#5a and #5c) to provide for alignment load of the line of compressive force with the segment's CFB.

iii. Moment application system: The application of moment, performed independently of the application of axial compressive load, followed the method of Panjabi. The force generated by the static weights (#8) was transferred via a braided cable through a load pully (# 9) to a loading bar (# 10). The loading bar is connected to each of the moment rings (# 11) via braided cables and steel lock rings. This arrangement ensured both self-alignment and equilibrium of the magnitude of the pull force between the moment rings. Adjusting the height of the load pully (# 9) through the linear lock-slides (# 12), and reversing the connection of the load bars, both forward (flexion) and backward (extension) pure moments were realized. Please note the device's 3DOF kinematical mechanism kept the development of coupled forces and moments due to possible imbalance of the forces used to affect the pure moment (force coupling at the pullies) to a minimum.

A.3. Creation of the lytic defect models. For this study, we chose to simulate two defect patterns of increased severity (Figure 4) reported to be associated with a high risk of vertebral failure (Tanechii et al. [28]). For the defect involving the vertebral body, we selected in the range of percent occupation of the body cross-sectional area reported to be the most clinically confounding for prediction of fracture [28]. Using a fluoroscopic unit (Mini 6600, GE medical, WI), each segment was mounted on an image registration jig and imaged to obtain axial and sagittal images of the segment's middle vertebra and the contours of the middle vertebra body along these planes transferred to individual transparency papers. The defect's location and geometry (as a percentage of the body cross-sectional area) was traced on each transparency. Under fluoroscopic control, a mechanical burr (5mm in diameter) attached to an electric rotary tool (Dremel MultiPro, Racine, WI) was used to create an entry portal within the lateral cortex of the segment's middle vertebra. An expanding reamer (X-REAM™ Percutaneous Expandable Reamer, Wright Medical, Memphis, TN) was introduced into the vertebral body, and the defect within the vertebral body established via careful manipulation of the location, depth, and size of the reamer. This procedure was continued until the cavity created matched the defect contours traced on both transparencies. For

defect pattern E, the mechanical burr was used under fluoroscopic control to extend the body defect (pattern C) by mechanically removing the ipsilateral pedicle and facet joint.

References

28. Taneichi H, Kaneda K, Takeda N, Abumi K, Satoh S. Risk factors and probability of vertebral body collapse in metastases of the thoracic and lumbar spine. Spine. 1997;22(3):239-45.
46. Bogduk N, Amevo B, Pearcy M. A biological basis for instantaneous centres of rotation of the vertebral column. Proc Inst Mech Eng H. 1995;209(3):177-83.
47. Patwardhan AG, Havey RM, Meade KP, Lee B, Dunlap B. A follower load increases the load-carrying capacity of the lumbar spine in compression. Spine (Phila Pa 1976). 1999;24(10):1003-9. doi: 10.1097/00007632-199905150-00014. PubMed PMID: 10332793.
48. Sis HL, Mannen EM, Wong BM, Cadel ES, Bouxsein ML, Anderson DE, Friis EA. Effect of follower load on motion and stiffness of the human thoracic spine with intact rib cage. J Biomech. 2016;49(14):3252-9. doi: 10.1016/j.jbiomech.2016.08.003. PubMed PMID: 27545081; PMCID: PMC5702885.

Table A.1. The effect of lesion models on the segment's range of motion (ROM) and translation motion parameters in response to the AC, AC+FL, and AC+EX mechanical tests.

K.parm.	Test	Control (n=13)	Model C	P	Control (n=11)	Model E	P
θx/Deg	AC	3.2 (2.7, 3.4)	3.2 (2.6, 3.4)		2.3 (1.7, 2.6)	3.1 (2.5, 3.9)	$
	AC+FL	-6.3 (-6.9, -5.4)	-7.8 (-8.2, -7.2)	$	-5.5 (-6.4, -5.2)	-7.3 (-8.5, -6.5)	&
	AC+ EX	6.6 (5.9, 7.4)	5.5 (4.3, 6.3)	$	5.5 (5.6, 8.1)	4.5 (2.6, 5.9)	$
θy/Deg	AC	0.1 (-0.1, 0.2)	0.1 (-0.1, 0.3)		0.1 (-0.2, 0.2)	0.4 (0.1, 0.6)	$
	AC+FL	-0.1 (-0.2, 0.5)	0.1 (-0.4, 0.2)		-0.5 (-1.0, 0.5)	-0.3 (-0.4, 0.6)	
	AC+ EX	-0.2 (-0.7, 0.4)	0.2 (-0.4, 0.7)		-0.2 (-1.0, 0.1)	0.1 (-0.1, 0.5)	*
θz/Deg	AC	0.1 (-0.1, 0.1)	0.1 (-0.1, 0.1)		0.1 (-0.2, 0.2)	0.2 (0.1, 0.3)	
	AC+FL	0.0 (-0.2, 0.4)	0.2 (-0.0, 0.4)		0.0 (-0.2, 0.1)	0.1 (-0.3, 0.3)	*
	AC+ EX	0.0 (-0.3, 0.4)	0.1 (-0.0, 0.3)		-0.3 (-0.4, -0.1)	0.4 (-0.0, 0.7)	*
Δx /mm	AC	0.2 (-0.2, 0.4)	0.3 (-0.0, 0.5)	*	0.0 (-04, 0.3)	0.5 (-0.1, 0.8)	&
	AC+FL	0.0 (-0.1, 0.2)	0.0 (-0.4, 0.4)		-0.3 (-0.5, -0.1)	-0.6 (-1.0, -0.4)	*
	AC+ EX	0.1 (-0.0, 0.2)	0.2 (-0.1, 0.3)		-0.1 (-0.3, 0.1)	0.3 (-0.1, 0.4)	*
Δy /mm	AC	1.3 (1.0, 1.5)	1.4 (1.0, 1.6)		0.9 (0.5, 1.4)	1.5 (1.0, 1.7)	$
	AC+FL	-0.5 (-1.0, 0.0)	-0.7 (-1.2, -0.0)		-0.5 (-1.2, 0.1)	-1.2 (-1.9, -0.3)	&
	AC+ EX	0.8 (-1.2, 1.7)	2.2 (1.4, 2.7)	&	0.9 (-1.1, 1.5)	2.0 (2.0, 2.5)	&
Δz /mm	AC	0.3 (0.1, 0.4)	0.3 (0.2, 0.70)		0.4 (0.2, 0.6)	0.73 (0.59, 1.0)	$
	AC+FL	0.4 (0.2, 0.4)	0.8 (0.6, 1.0)	&	0.3 (0.2, 0.5)	0.8 (0.7, 1.2)	&
	AC+ EX	-0.3 (-0.4, -0.2)	-0.7 (-0.9, -0.5)	&	-0.3 (-0.5, -0.2)	-0.8 (-1.1, -0.4)	&

All values are presented as median (q1-q3).
Statistical comparisons; *: $p<0.05$; #: $p<0.01$; &: $p< 0.0001$. $: $p< 0.0001$.
K.parm.: Kinematic parameter: Øx: lateral bending angle, Øy: Flexion/extension angle, θz: Torsional angle. ΔX: Sagittal translation: Δy: transverse translations, Δz: Axial translation.