

Fig. E-1A

Disc regions. Vertebral body end plates were partitioned into posterior anulus (green), nucleus (teal), and anterior anulus (red) regions. Disc height measurements were acquired and averaged over the central one-third of the disc width (between dotted lines).

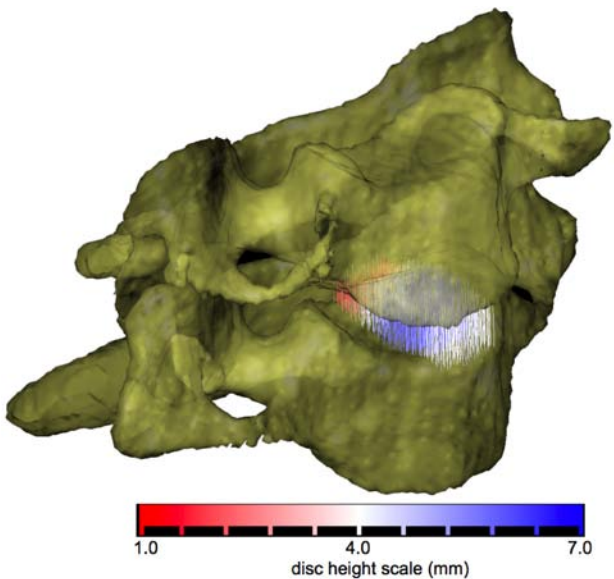


Fig. E-1B

Color-coded disc height on a C6/C7 motion segment. Disc height was measured over several hundred points for each disc. The average height of all line segments within each disc region represented the disc height within that region. Line segments representing disc height are color-coded from 1 mm (red) to 7 mm (blue).

TABLE E-1 Subject Demographic and Surgical Details

Group	Subjects*	Age† (yr)	Sex*	Time Postsurgery† (mo)	Arthrodesis Plate*	Graft Type*	Smoking Status*
Control	20	45.5 ± 5.8	7 M, 13 F	Not applic.	Not applic.	Not applic.	5 smoker, 10 never smoked, 5 quit
C5/C6 arthrodesis	10	45.3 ± 9.1	2 M, 8 F	6.9 ± 1.2	7 Medtronic Atlantis (Minneapolis, MN), 2 DePuy Skyline (Raynham, MA), 1 Abbott Spine (Austin, TX)	7 autograft, 3 allograft	5 smoker, 2 never smoked, 3 quit

\*The values are given as the number of subjects. †The values are given as the mean and standard deviation.

TABLE E-2 Anterior and Posterior Translation Ranges of Motion (in Millimeters) During Dynamic Flexion-Extension\*

Group	C2/C3		C3/C4		C4/C5		C5/C6		C6/C7	
	Ant	Post	Ant	Post	Ant	Post	Ant	Post	Ant	Post
Control†	2.2 ± 1.0	1.7 ± 1.0	2.0 ± 1.1	1.7 ± 0.9	1.9 ± 0.8	2.0 ± 0.8	1.6 ± 0.7	1.5 ± 1.0	1.4 ± 0.8	1.0 ± 0.5
C5/C6 arthrodesis†	N/A	N/A	1.6 ± 1.1	2.0 ± 0.7	1.7 ± 1.4	2.7 ± 1.3	0.4 ± 0.3*	0.3 ± 0.3*	1.2 ± 0.8	1.4 ± 0.5*
Difference	N/A	N/A	-0.4	0.3	-0.2	0.8	-1.2	-1.3	-0.1	0.4
95% CI‡	N/A	N/A	-1.2 to 0.5	-0.3 to 1.0	-1.0 to 0.6	0.0 to 1.6	-1.6 to -0.9	-1.7 to -0.8	-0.8 to 0.5	0.0 to 0.8

\*No significant differences between anterior and posterior ranges of motion were identified in the control group or arthrodesis group at any motion segment. The following significant differences between the control and arthrodesis groups were identified (marked by asterisks within the table): C5/C6 (anterior): control > arthrodesis (p < 0.001); C5/C6 (posterior): control > arthrodesis (p < 0.001); and C6/C7 (posterior): control < arthrodesis (p = 0.016). N/A = not available. †The values are given as the mean and standard deviation. ‡The 95% confidence interval of the difference between groups.

TABLE E-3 Clinical Anterior-Posterior Translation Range of Motion (in Millimeters) During Dynamic Flexion-Extension\*

Group	C2/C3	C3/C4	C4/C5	C5/C6	C6/C7
Control†	2.0 ± 0.5	2.3 ± 0.6	2.3 ± 0.6	1.7 ± 0.8	1.1 ± 0.6
C5/C6 arthrodesis†	N/A	2.3 ± 0.4	2.8 ± 0.8	0.6 ± 0.3*	1.3 ± 0.3
Difference	N/A	0.0	0.5	-1.0	0.2
95% CI‡	N/A	-0.4 to 0.4	-0.1 to 1.0	-1.5 to -0.6	-0.2 to 0.6

\*The following significant difference between the control and arthrodesis groups was identified (marked by asterisk within the table): C5/C6: control > arthrodesis (p < 0.001). N/A = not available. †The values are given as the mean and standard deviation. ‡The 95% confidence interval of the difference between groups.

TABLE E-4 Differences Between Dynamic and Static Rotation Ranges of Motion (in Degrees) During Flexion-Extension\*

Group	C2/C3			C3/C4			C4/C5			C5/C6			C6/C7		
	Flex-Ext	Twist	Lat Bend	Flex-Ext	Twist	Lat Bend	Flex-Ext	Twist	Lat Bend	Flex-Ext	Twist	Lat Bend	Flex-Ext	Twist	Lat Bend
Control†	<b>1.1 ± 0.6</b>	<b>1.3 ± 0.6</b>	<b>1.2 ± 0.6</b>	<b>0.9 ± 1.1</b>	<b>1.1 ± 1.0</b>	<b>1.5 ± 1.2</b>	<b>1.2 ± 1.9</b>	<b>1.0 ± 0.5</b>	<b>1.5 ± 0.9</b>	0.4 ± 2.4	<b>1.0 ± 0.8</b>	<b>1.2 ± 0.7</b>	-0.3 ± 4.0	0.6 ± 1.2	<b>1.1 ± 1.1</b>
C5/C6 arthrodesis†	N/A	N/A	N/A	3.1 ± 4.1	<b>1.4 ± 0.6</b>	<b>1.4 ± 1.1</b>	<b>2.8 ± 2.9</b>	<b>2.1 ± 1.2</b>	<b>2.0 ± 1.7</b>	<b>1.8 ± 0.9</b>	<b>0.9 ± 1.0</b>	<b>1.8 ± 0.9</b>	1.6 ± 2.1	1.2 ± 1.4	<b>2.0 ± 1.4</b>
95% CI‡	0.9 to 1.5	0.9 to 1.5	0.9 to 2.2	0.5 to 3.1	0.9 to 1.6	1.0 to 2.1	0.8 to 2.7	0.9 to 2.1	1.0 to 2.3	0.7 to 1.8	-0.1 to 2.0	1.1 to 2.2	-1.4 to 1.9	0.2 to 1.7	0.9 to 2.2

\*No significant differences between the control and arthrodesis groups were identified. Bold text indicates significant within-subject differences between static and dynamic rotation ranges of motion. Positive values indicate an increased range of motion during dynamic trials. N/A = not available. †The values are given as the mean and standard deviation. ‡The 95% confidence interval of the difference between the dynamic and static ranges of motion for the control and arthrodesis groups combined.

TABLE E-5 Differences Between Dynamic and Static Translation Ranges of Motion (in Millimeters) During Flexion-Extension\*

Group	C2/C3			C3/C4			C4/C5			C5/C6			C6/C7		
	Med-Lat	Sup-Inf	Ant-Post	Med-Lat	Sup-Inf	Ant-Post	Med-Lat	Sup-Inf	Ant-Post	Med-Lat	Sup-Inf	Ant-Post	Med-Lat	Sup-Inf	Ant-Post
Control†	<b>0.3 ± 0.2</b>	<b>0.3 ± 0.2</b>	<b>0.4 ± 0.3</b>	<b>0.4 ± 0.3</b>	<b>0.3 ± 0.3</b>	<b>0.2 ± 0.3</b>	<b>0.4 ± 0.4</b>	<b>0.3 ± 0.2</b>	<b>0.2 ± 0.3</b>	<b>0.4 ± 0.3</b>	<b>0.2 ± 0.3</b>	<b>0.0 ± 0.6</b>	<b>0.3 ± 0.2</b>	<b>0.3 ± 0.4</b>	-0.1 ± 0.8
C5/C6 arthrodesis†	N/A	N/A	N/A	<b>0.5 ± 0.4</b>	<b>0.4 ± 0.3</b>	0.8 ± 1.0	<b>0.4 ± 0.2</b>	<b>0.7 ± 0.7</b>	0.8 ± 1.2	<b>0.6 ± 0.5</b>	<b>0.6 ± 0.3</b>	0.2 ± 0.4	<b>0.7 ± 0.4*</b>	<b>0.6 ± 0.3</b>	<b>0.7 ± 0.6</b>
95% CI‡	0.2 to 0.5	0.2 to 0.4	0.2 to 0.5	0.3 to 0.6	0.2 to 0.5	0.1 to 0.7	0.3 to 0.5	0.3 to 0.6	0.1 to 0.8	0.3 to 0.6	0.2 to 0.5	-0.1 to 0.3	0.3 to 0.5	0.3 to 0.6	-0.1 to 0.5

\*The following significant difference between the control and arthrodesis groups was identified (marked by asterisk within the table): C6/C7 (medial-lateral): control < arthrodesis (p = 0.002). Bold text indicates significant within-subject differences between static and dynamic rotation ranges of motion. Positive values indicate an increased range of motion during dynamic trials. N/A = not available. †The values are given as the mean and standard deviation. ‡The 95% confidence interval of the difference between the dynamic and static ranges of motion for the control and arthrodesis groups combined.

TABLE E-6 Trial-to-Trial Variability in Rotation Range of Motion (in Degrees) During Dynamic Flexion-Extension\*

Group	C2/C3			C3/C4			C4/C5			C5/C6			C6/C7		
	Flex-Ext	Twist	Lat Bend	Flex-Ext	Twist	Lat Bend	Flex-Ext	Twist	Lat Bend	Flex-Ext	Twist	Lat Bend	Flex-Ext	Twist	Lat Bend
Control	0.4	0.3	0.3	0.6	0.2	0.4	0.6	0.2	0.4	0.6	0.2	0.3	0.9	0.3	0.4
C5/C6 arthrodesis	N/A	N/A	N/A	0.8	0.3	0.4	0.8	0.3	0.4	0.5	0.4	0.3	1.2	0.5	0.6

\*No significant differences between the control and arthrodesis groups were identified. N/A = not available.

TABLE E-7 Trial-to-Trial Variability in Translation Range of Motion (in Millimeters) During Dynamic Flexion-Extension\*

Group	C2/C3			C3/C4			C4/C5			C5/C6			C6/C7		
	Med-Lat	Sup-Inf	Ant-Post	Med-Lat	Sup-Inf	Ant-Post	Med-Lat	Sup-Inf	Ant-Post	Med-Lat	Sup-Inf	Ant-Post	Med-Lat	Sup-Inf	Ant-Post
Control	0.10	0.07	0.16	0.08	0.08	0.16	0.11	0.08	0.13	0.09	0.11	0.13	0.10	0.15	0.22
C5/C6 arthrodesis	N/A	N/A	N/A	0.15	0.10	0.13	0.11	0.14	0.22	0.24	0.13	0.13	0.31*	0.17	0.33

\*The following significant difference between the control and arthrodesis groups was identified (marked by asterisk within the table): C6/C7 (medial-lateral): control < arthrodesis ( $p < 0.001$ ). N/A = not available

TABLE E-8 Disc Height by Vertebral Level and Anatomic Location\*

Group	C2/C3			C3/C4			C4/C5			C5/C6			C6/C7		
	Ant Anulus	Nucleus	Post Anulus	Ant Anulus	Nucleus	Post Anulus	Ant Anulus	Nucleus	Post Anulus	Ant Anulus	Nucleus	Post Anulus	Ant Anulus	Nucleus	Post Anulus
Control†	4.0 ± 0.9	4.6 ± 0.7	3.3 ± 0.5	3.9 ± 0.6	4.4 ± 0.7	3.0 ± 0.6	4.0 ± 1.0	4.4 ± 0.8	3.1 ± 0.6	3.6 ± 1.1	4.0 ± 1.2	2.7 ± 1.0	3.8 ± 1.3	4.4 ± 1.3	3.0 ± 1.1
C5/C6 arthrodesis †	N/A	N/A	N/A	4.3 ± 0.9	4.8 ± 0.5	3.2 ± 0.7	4.3 ± 0.9	4.7 ± 0.9	3.8 ± 0.9	N/A	N/A	N/A	4.5 ± 0.8	5.2 ± 0.5	3.9 ± 0.6
Difference	N/A	N/A	N/A	0.4	0.4	0.2	0.3	0.3	0.8	N/A	N/A	N/A	0.7	0.8	0.9
95% CI‡	N/A	N/A	N/A	-0.2 to 1.0	-0.1 to 0.9	-0.3 to 0.7	-0.5 to 1.0	-0.4 to 1.0	0.2 to 1.3	N/A	N/A	N/A	-0.3 to 1.6	-0.1 to 1.7	0.2 to 1.7

\*In the control subjects, no differences in disc height were observed among disc levels ( $p = 0.253$ ), but significant differences in disc height were observed among disc regions: nucleus > anterior anulus ( $p = 0.001$ ), nucleus > posterior anulus ( $p < 0.001$ ), and anterior anulus > posterior anulus ( $p < 0.001$ ). N/A = not available. No significant differences between the control and arthrodesis groups were identified. †The values are given as the mean and standard deviation. ‡The 95% confidence interval of the difference between groups.

## Appendix

### *Disc Height Calculations*

Nucleus and anulus regions were defined on the bone-model end-plate surfaces according to the method used in previous reports<sup>49,50</sup>, and disc height measurements were acquired within the central one-third of the disc width (Fig. E1-A). The average disc height within the nucleus, anterior anulus, and posterior anulus regions was determined from the static trial with the subject holding the head in an upright neutral position (Fig. E1-B).

### *Trial-to-Trial Variability Results*

Average trial-to-trial variability in maximum rotation range of motion (defined as the standard deviation of the maximum range of motion for all trials for a given subject) was  $\leq 0.9^\circ$  for all three rotational degrees of freedom in the control subjects (Table E-6) during the dynamic trials. Variability was consistently greater in flexion-extension rotation ( $0.4^\circ$  to  $0.9^\circ$ ) than in twist or lateral bend rotation ( $0.2^\circ$  to  $0.4^\circ$ ) for the control subjects. Trial-to-trial variability in the rotation range of motion did not differ significantly between the control and arthrodesis groups (all  $p > 0.056$ ).

Trial-to-trial variability in maximum translation range of motion was  $\leq 0.22$  mm for all three translational degrees of freedom in the control subjects (Table E-7) during dynamic trials. The C5/C6 arthrodesis group was observed to have significantly greater variability in the medial-lateral direction inferior to the fused segment in comparison with the controls ( $p < 0.001$ ).

### *Disc Height Results*

No differences in disc height were identified among the disc levels in the control subjects ( $p = 0.253$ ); however, significant differences were observed among disc regions (Table E-8). Nucleus height was significantly greater than anterior anulus height and posterior anulus height ( $p = 0.001$  and  $p < 0.001$ , respectively), while anterior anulus height was significantly greater than posterior anulus height ( $p < 0.001$ ). Differences between the arthrodesis and control group disc heights were further reduced when corrected for bone size.

### *Trial-to-Trial Variability Discussion*

When reporting in vivo kinematic data, it is beneficial to be aware of the trial-to-trial variability within subjects. Increased trial-to-trial variability may indicate joint instability or a deficit in neuromuscular control. Furthermore, for research purposes, it is helpful to know how well a single movement trial represents the typical movement being analyzed. The results of the current study indicate that range-of-motion measurements during flexion-extension are highly repeatable for subjects when the described protocol and measurement techniques are used. This finding suggests, first, that subjects are capable of performing the flexion-extension movement in a highly repeatable fashion and, second, that the measurement tools used to characterize the motion have high precision. We are not aware of any previous studies in which the investigators collected and analyzed multiple trials from each subject to assess within-subject variability in cervical spine range of motion. The variability results presented here provide a standard that potentially can be used to identify cervical spine instability during dynamic, functional movement.