1 **Effects of Standing on Spinal Alignment and Lumbar Intervertebral Discs in Young, Healthy**

2 **Individuals Determined by Positional Magnetic Resonance Imaging**

3

4

5 Christian I. Weber[1], Ching-Ting Hwang[2], Linda R. Van Dillen[2,3,4], Simon Y. Tang[1,4]

6 [1]Biomedical Engineering; [2]Movement Science Program; [3]Physical Therapy; [4]Orthopaedic Surgery

7 Washington University in St. Louis, St. Louis, MO

8 Running head: Effects of Standing on Spinal Alignment and Lumbar IVDs
9
10 Corresponding author:
11 Simon Y. Tang, Ph.D.
12 660 South Euclid Ave, Box 8233
13 St. Louis, MO 63110
14 (314) 286-2664
15 simon.tang@wustl.edu
16
18
19
20
21
22

23 **Abstract**

24 Traditional diagnostic imaging of the spine is performed in supine, a relatively unloaded position.

25 However, the spine is subjected to complex loading environments in daily activities such as standing.

26 Therefore, we seek to quantify the changes from supine to standing in the spines of young, healthy

27 individuals in standing using a positional MRI system. This is an observational study that examined the

28 changes in the spine and individual intervertebral discs (IVDs) during supine and standing of forty healthy

29 participants (19 males / 21 females) without a history of low back pain. The regional lumbar spinal

30 alignment was measured by the sagittal Cobb angle. Segmental IVD measurements included the segmental

31 Cobb angle, anterior to posterior height (A/P) ratio, and IVD width measured at each L1/L2 - L5/S1 levels.

32 The intra-observer intra-class correlation (ICC) consistency model showed values for measurements ranged

33 from 0.76-0.98. The inter-observer ICC values ranged from 0.68-0.99. The Cobb angle decreased in

34 standing. The L5/S1 segmental Cobb angle decreased in standing. The L2/L3 and L3/L4 A/P ratios

35 increased and the L5/S1 A/P ratio decreased in standing. No differences in IVD width were observed from

36 supine to standing. This study examined the regional lumbar spinal alignment and segmental IVD changes

37 from supine to standing in young, healthy individuals without LBP using pMRI. In developing and

38 validating these measurements, we have also established the normative data for healthy, asymptomatic

39 population that could be useful for other investigations examining how individuals with spinal or IVD

40 pathologies may adapt between supine and standing.

Introduction

41

42 The degeneration of the intervertebral disc (IVD) is a significant contributor to low back pain (LBP) (39) .

43 Despite the association between IVD degeneration and LBP, the correspondence between the clinical

44 presentation of LBP and IVD imaging findings is quite poor (35). One possibility for this lack of specificity

45 may be that most diagnostic imaging of the spine is performed in supine, a minimally loaded position (5,

46 45). An individual in standing generates lumbar intradiscal pressures approximately five times greater

47 than in supine (31) and complex multiaxial forces (32) that result in different tensile and shear deformations

48 across the IVD (3, 43). Compressive loading similar to that experienced during standing is critical for

49 maintaining spinal curvature (44). Thus, examining the spine in standing may be more functionally and

50 clinically relevant than in supine.

51 Magnetic Resonance Imaging (MRI) is a commonly used radiographic technique for the imaging of

52 the spine and for the visualization of hydrated tissue structures such as the IVDs. Positional MRI (pMRI)

53 with an open magnet configuration enables the imaging of the human participants in different positions (4,

54 18, 19); thus, the pMRI provides the opportunity to observe the spinal structures in loaded positions other

55 than supine (6, 18, 36, 37). Examining the lumbar spine in an upright position using a pMRI has improved

56 the specificity in discriminating acute and chronic LBP populations (42) and increased the reliability of

57 observing stenosis and IVD degeneration (12). Prior studies have utilized pMRI to examine spinal

58 adaptations between sitting to standing (20), supine to standing in athletes (29) and patients with lumbar

59 spinal stenosis (27), and changes of the dural sac in the lumbar spine due to posture (16). But none of these

60 studies explored differences of segmental structural measurements from supine to standing in a young,

61 healthy population without a history of LBP ('back-healthy'). Back-healthy individuals have been shown

62 to be susceptible to LBP symptoms in prolonged standing with a high rate of developing chronic LBP (9,

63 10, 28, 33, 34, 40). Thus examining the standing-induced adaptations in the back-healthy population could

64 provide predictive information prior to development of spinal pathologies. The pMRI can leveraged to

65 observe adaptations across positions of the lumbar spine using regional alignment measurements (sagittal

66 Cobb angle) and segmental lumbar measurements such as segmental Cobb angle, anterior/posterior height

67 (A/P) ratio, and IVD width. Therefore, the objectives of this study are to 1) investigate the effects of

68 standing on the spinal alignment and individual lumbar IVDs of young, back-healthy human participants

69 ranging from 18 to 30 years of age using pMRI, and 2) determine whether there are sex-specific differences

70 in these measurements due to the variations in spinal alignment between males and females (15, 47). We

71 hypothesized that 1) the sagittal Cobb angle would be significantly different between supine and standing,

72 2) individual IVDs across the lumbar spine would adapt differentially to standing, and 3) the change in

73 segmental Cobb angle, A/P ratio, and IVD width at each lumbar level from supine to standing would be

74 different between males and females.

75   **Material and methods**

76   *Participants*

77   The study included forty participants (19 male/21 female) between 18-30 years of age and body-mass index

78   (BMI) $< 30 kg/m^2$ (Table 1). Participants were recruited through posted flyers and distributed emails to the

79   community and local universities in the St. Louis metropolitan area. Participants were excluded during

80   screening if they reported any history of LBP. LBP was defined as pain in the lumbar region greater than

81   2 on a 0-10 verbal numeric rating scale that lasted at least 24 hours that resulted in one or more of the

82   following: (1) some type of medical intervention (e.g., physician, physical therapist, chiropractor); (2) three

83   or more consecutive days of missed work or school; (3) three of more consecutive days of altered activities

84   of daily living. Exclusion criteria also included a prior diagnosis of diabetes, anxiety, depression,

85   employment in a job that involved standing for greater than 4 hours per day or standing in one place for

86   more than 1 hour per day during the last 12 months, consumption of caffeinated drinks > 25 per week,

87   consumption of alcoholic drinks > 10 per week, or smoking cigarettes > 15 per day. All participants read

88   and signed an informed consent form in accordance with the Human Research Protection Office at

89   Washington University School of Medicine. The participants were instructed to avoid non-habitual

90   strenuous physical activity (e.g., running, weight lifting) for 24 hours prior to imaging with no rescheduling

91   required. All imaging was performed in the afternoon after 12PM to minimize diurnal variations (26).

92

93   *Data collection*

94   Images of the lumbar spine (L1-S1) were obtained using the 0.6T Open UPRIGHT® MRI (Fonar, New

95   York, NY) system. A 3-plane localizer was used to acquire sagittal T2 weighted images (repetition time =

96   610 ms, echo time = 17 ms, field of view = 24 cm, acquisition matrix = 210 x 210, slice thickness = 3 mm,

97   no gap, scan duration = 2 min) (37). This sequence was optimized for reducing scan time and motion

98   artifacts [12-13]. A wood plank was placed adjacent to the quad-planar coil on the MRI table to provide a

99   continuous flat surface for the lumbar spine (Fig. 1). The participant entered the scanner facing forward

100   with his/her back against the table. A pillow was placed behind the head to provide support to the neck.

101   The table was adjusted to a horizontal position of 180 degrees. The participant was positioned in supine for

102   10 minutes prior to the first scan. The MRI table then was moved to a vertical position with a 84 degree

103   table tilt where participants were then standing. The table tilt of 84 degrees helped to stabilize the

104   participant and prevent motion artifacts during the imaging in standing (Fig. 1). The pillow was removed,

105   and a VersaRest^{TM} device, an arm support, was placed in the scanner underneath the wrists 5 cm below the

106   lateral epicondyle of the elbow (Fig. 1). Participants were told to stand normally without leaning on the

107   sides of the magnet, back of the scanner or on the VersaRest^{TM} during the scan in standing. A board-

108   certified MRI technician conducted all imaging. After imaging, all images were exported as DICOM files

109   to be analyzed on Miele (OsiriX)-LXIV (open source) (38).

110

111   *Regional Lumbar Spine Alignment*

112   The four-line Cobb method, denoted here as the Cobb angle, was used to quantify regional lumbar spine

113   alignment (14). The Cobb angle was measured between the inferior T12 and superior S1 endplates (Fig.

114   2A). This measurement was obtained in supine and standing for each participant using the mid-sagittal slice

115   of the MR image.

116

117   *Segmental IVD Measurements*

118   The measures for each of the five lumbar IVDs, L1/L2 through L5/S1, were obtained in supine and standing

119   for each participant using the mid-sagittal slice of the MR image. The measures included the segmental

120   Cobb angle, the anterior to posterior height (A/P) ratio, and the IVD width (Fig. 2B, 2C and 2D). The

121   segmental Cobb angle was calculated as the angle created by the line segment containing the anterior and

122   posterior edges of the superior endplate with the line segment containing anterior and posterior side of the

123   inferior endplate (Fig. 2B). The heights were calculated as the distances on the superior endplate to inferior

124   endplate distance at the anterior and posterior sides for each IVD level. The A/P ratio was calculated by

125   dividing the anterior height by the posterior height (Fig. 2C). The IVD width was defined as the maximum

126   distance between the anterior and posterior bulge points of an IVD in a sagittal view (Fig. 2D).

127

128 *Reproducibility, error and uncertainty*

129 The intra-observer (C.W./researcher) and inter-observer (researchers) reproducibility were indexed with

130 the Intraclass Correlation Coefficient (ICC) using data from participants that exhibited the greatest range

131 of values for regional and all lumbar segments (30). A written rubric based on anatomical landmarks

132 (segmental Cobb angles, IVD widths, the anterior-, and posterior- heights) was used for all segmental

133 measurements. The intra-observer analysis was performed using measured variables obtained on three

134 distinct nonconsecutive days. Additional observers performed the inter-observer analysis based on the

135 written rubric for regional and segmental measurements with three sets of measurements on non-

136 consecutive days.

137 We quantified the error associated with image resolution and its impact on the uncertainty of IVD

138 measurements. The resolution-based error of the MRI images was determined by moving the coordinates

139 of each anatomical landmark in every possible direction and calculating the effect on the subsequent IVD

140 measurements. The maximum uncertainty from resolution on the measurements using this combinatorial

141 approach were 5.2%, 5.4%, and 1.3% for segmental Cobb angle, A/P ratio, and IVD width, respectively.

142

143 *Statistical Analyses*

144 A three-way, repeated measures analysis of variance (ANOVA) was used to test for the factors of position,

145 sex, and lumbar level for each of the three segmental measurements (segmental Cobb angles, A/P ratios,

146 and IVD widths). Cobb angle was analyzed using a two-way repeated measures ANOVA to test for the

147 factors of position and sex. Interaction terms are denoted by an asterisk (*) in Table 2 and in the results.

148 Post-hoc comparisons were done using the Fisher's least significant difference test. Differences are

149 significant when the associated p-value is ≤ 0.05. Post-hoc power analysis was performed on significant

150 results using G*Power (8).

151

152

153 **Results**

154   All enrolled participants (n = 40) completed the supine and standing imaging sessions and were

155 included in all analyses.

156

157 *Reliability of Measurements*

158   Figure 3 shows intra-observer ICC values for each measurement. The ICC values (with the 95%

159 confidence interval in parentheses) for the segmental Cobb angle, IVD width, and the anterior and posterior

160 height measurements were 0.90 (0.79-0.96), 0.98 (0.95-0.99), 0.89 (0.78-0.95), and 0.76 (0.58-0.89)

161 respectively. The inter-observer ICC agreement for segmental Cobb angle, IVD width, and the anterior and

162 posterior height measurements were 0.89 (0.79 – 0.95), 0.99 (0.98 – 1), 0.84 (0.7 – 0.93), and 0.68 (0.46 –

163 0.85), respectively. The intra-observer ICC for Cobb angle was 0.97 (0.90 – 0.99), and the inter-observer

164 ICC was 0.87 (0.61-0.97).

165

166 *Regional Lumbar Spine Alignment*

167   Position was a significant factor. The Cobb angle decreased in standing compared to supine for all

168 participants (Fig. 4; $p < 0.05$).

169

170 *Segmental IVD Measurements*

171 <u>Segmental Cobb Angle</u>

172 Sex, level, and level*position all were significant factors (Table 2). Post hoc analyses revealed that

173 compared to supine the L5/S1 segmental Cobb angle decreased in standing (Fig. 5; $p < 0.05$).

174 <u>A/P ratio</u>

175 Sex, level, position, and level*position were significant factors (Table 2). Compared to supine the L2/L3

176 and L3/L4 A/P ratio increased in standing ($p < 0.05$), and the L5/S1 A/P ratio decreased in standing (Fig.

177 6; $p < 0.05$).

178 <u>IVD Width</u>

179   Sex, level, position, and level*position were significant factors (Table 2). There were no significant

180   differences in IVD width due to positions at lumbar levels L1/L2 to L4/L5 for all participants (Fig. 7).

181   Although the L5/S1 IVD width in standing was statistically greater than in supine ($p < 0.05$), the margin of

182   the difference (0.48%) was below the detection threshold per our error analyses (1.3%), and thus we did

183   not consider this difference to be meaningful.

Discussion

To our knowledge this is the first study to examine the segmental Cobb angle, A/P ratio and IVD width from supine to standing. In contrast to other studies that examined angular changes that included the vertebrae and the adjacent IVD (23, 46), we measured the changes between the inferior and superior vertebral endplates of individual discs (1, 17) enabling observation of IVD-specific adaptations at every lumbar level. pMRI studies on Marine populations have shown that individual IVDs adapt to external loads placed on the spine in standing (6, 37). The changes in segmental IVD measurements from supine to standing in our back-healthy group show that adaptations due to increased loading occur at multiple levels of the lumbar spine, similar to the externally loaded spine in the supine position (21). The ability of these lumbar levels to adapt may be important for the spine to distribute loads, especially when the diminished ability of individual lumbar levels to adapt to loading are concomitant with disease and degeneration (6, 22). Given that the pMRI in standing improves the detection of IVD bulging (49), the lack of bulging in these participants in standing confirms that these IVDs are indeed relatively healthy (2, 41).

The reduced lordosis of our participants in standing is consistent with the observations of another pMRI study (27). Other studies using a pMRI have shown that lordosis is not different between supine and standing with a cushion underneath their knees (16). These results are in contrast with studies done using plain film radiography which observed more lordosis in standing (7, 23, 46). The discrepancy is likely due to a pelvic tilt that has been shown to influence lumbar lordosis in standing (24), since the pelvis is strongly correlated to lumbar lordosis in supine (7). In this study, we did not directly control for pelvic tilt by placing a pillow underneath the legs in supine. Despite this, our measured Cobb angles in standing are consistent with a prior report that also included young, asymptomatic individuals (48). Further, it has been shown that externally applied loads during standing can alter the lumbar spine to be in less lordosis in pMRI (6, 36, 37). Our study did not find lordosis to be different between sexes as previously reported (15, 47). Additionally, we observed that males and females comparably change from supine to standing. Wood et al. included males and females in their study but did not specifically report on sex differences in position (46). Although we observed sex as a significant factor in the segmental measurements, there were no interactions

210 between sex and position, suggesting though both sexes adapt to standing, they do not adapt differently. In

211 this study, the decline of the Cobb angle of the spine in standing in a young, back-healthy group with no

212 observed translational lumbosacral anatomies or spondylolysis/spondylolisthesis is coupled with

213 measurable changes in the IVD across the different lumbar levels (Fig. 5, 6).

214   Characterizing the IVD using measurements that are based on independent landmarks is important

215 for capturing the nuanced changes in the structure of the IVD (12, 16, 42). Using the pMRI system, we

216 demonstrate that it is possible to determine and reliably characterize the regional lumbar alignment and

217 individual lumbar IVDs using the segmental measurements of segmental Cobb angle, A/P ratio, and IVD

218 width. Moreover, the images obtained in standing can yield more physiologically relevant information than

219 a slightly higher resolution scan taken in supine due to the differences in loading between supine and

220 standing. Although some of the measurements made here could also be obtained from plain film

221 radiographs (23, 25), the pMRI enables the possibility of assessing any potential involvement of IVD-

222 specific pathologies (such as herniations) in the spinal structural measurements. The nature of MRI also

223 leverages the increased signal of hydrated microstructures in the IVD, and the 3D reconstruction capabilities

224 of the volumetric image stack could be utilized further for additional spatially-unbiased analyses.

225   There are several limitations to our study. First, although the field strength of this pMRI system

226 (0.6 T) is lower than typical clinical systems (1.5 T), the higher efficiency of the field algorithm reconstructs

227 and generates images at comparable resolutions to 1.5 T systems (13). The ICC and uncertainty analyses

228 confirm the reliability of our measurements using the pMRI system. Our inter-observer reliability ranged

229 from 0.68 to 0.99 and is consistent with a MRI study that reported an inter-observer ICC range of 0.73-0.95

230 (11). Analyses of error and uncertainty in our images reveal that the resolution can affect the measurements

231 by 1.3%-5.4%, and thus only differences that were greater than the uncertainty range were considered to be

232 meaningful. Second, we did not directly control for the pelvic tilt which is known to influence spinal

233 alignment, and this may have contributed to the participants' variations in the supine spinal alignment.

234 Third, although we only enrolled 40 participants in this study, the power for our discriminating

235   measurements ranged from 0.57-0.99, indicating that the sample size is adequate for most measures. Only

236   the L3/L4 A/P ratio was powered below 0.80 at 0.57.

237   This study is the first to examine the differences in regional and segmental measurements between

238   supine and standing positions in young, back-healthy participants using a pMRI system. Further, we have

239   developed and validated a method using the pMRI system to evaluate changes in spinal measurements. Our

240   key finding here is that the individual IVD levels within a healthy spine adapt to loaded positions non-

241   uniformly. These findings highlight the importance of acquiring images in standing as they are different

242   than the traditional MRI images in supine. Observing IVDs in standing and comparing symptomatic and

243   asymptomatic individuals can be more informative of IVD function and help elucidate the discordance

244   between imaging findings and LBP.

245 **Acknowledgements**

246 The authors gratefully acknowledge Dave Magner, Travis Gould, Nicholas Woerther and the staff at The

247 Open Upright MRI of Missouri for providing technical assistance with the imaging.

248 **Grants**

249 These studies were supported by the National Institutes of Health (P30 AR57325 - WUSTL

250 Musculoskeletal Research Center), K01AR069116, R21AR069804, and 5T32EB018266.

251 **Disclosures**

252 The authors have no conflicts of interest.

References

1. **Acosta FL**, **Liu J**, **Slimack N**, **Moller D**, **Fessler R**, **Koski T**. Changes in coronal and sagittal plane alignment following minimally invasive direct lateral interbody fusion for the treatment of degenerative lumbar disease in adults: a radiographic study. *J Neurosurg Spine* 15: 92–96, 2011.

2. **Adams MA**, **Freeman BJC**, **Morrison HP**, **Nelson IW**, **Dolan P**. Mechanical Initiation of Intervertebral Disc Degeneration [Online]. *Spine* 25, 2000. http://journals.lww.com/spinejournal/Fulltext/2000/07010/Mechanical_Initiation_of_Intervertebr al_Disc.5.aspx.

3. **Aiyangar AK**, **Zheng L**, **Tashman S**, **Anderst WJ**, **Zhang X**. Capturing Three-Dimensional In Vivo Lumbar Intervertebral Joint Kinematics Using Dynamic Stereo-X-Ray Imaging. *J Biomech Eng* 136: 011004-011004–9, 2013.

4. **Alyas F**, **Connell D**, **Saifuddin A**. Upright positional MRI of the lumbar spine. *Clin Radiol* 63: 1035–1048, 2008.

5. **Baker ADL**. Abnormal Magnetic-Resonance Scans of the Lumbar Spine in Asymptomatic Subjects. A Prospective Investigation. In: *Classic Papers in Orthopaedics*, edited by Banaszkiewicz PA, Kader DF. Springer London, p. 245–247.

6. **Berry DB**, **Rodríguez-Soto AE**, **Su J**, **Gombatto SP**, **Shahidi B**, **Palombo L**, **Chung C**, **Jensen A**, **Kelly KR**, **Ward SR**. Lumbar spine postures in marines during simulated operational positions. *J. Orthop. Res.* (January 1, 2017). doi: 10.1002/jor.23510.

7. **Chevillotte T**, **Coudert P**, **Cawley D**, **Bouloussa H**, **Mazas S**, **Boissière L**, **Gille O**. Influence of posture on relationships between pelvic parameters and lumbar lordosis: Comparison of the standing, seated, and supine positions. A preliminary study. *Orthop Traumatol Surg Res* 104: 565–568, 2018.

8. **Faul F**, **Erdfelder E**, **Lang A-G**, **Buchner A**. G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behav Res Methods* 39: 175–191, 2007.

9. **Gallagher KM**, **Callaghan JP**. Early static standing is associated with prolonged standing induced low back pain. *Hum Mov Sci* 44: 111–121, 2015.

10. **Gregory DE**, **Callaghan JP**. Prolonged standing as a precursor for the development of low back discomfort: An investigation of possible mechanisms. *Gait Posture* 28: 86–92, 2008.

11. **Guen YL**, **Joon WL**, **Hee SC**, **Kyoung-Jin O**, **Heung SK**. A new grading system of lumbar central canal stenosis on MRI: an easy and reliable method. *Skeletal Radiol* 40: 1033–1039, 2011.

12. **Hansen BB**, **Hansen P**, **Christensen AF**, **Trampedach C**, **Rasti Z**, **Bliddal H**, **Boesen M**. Reliability of standing weight-bearing (0.25T) MR imaging findings and positional changes in the lumbar spine. *Skeletal Radiol* 47: 25–35, 2018.

13. **Hansson L**, **Westesson P**, **Katzberg R**, **Tallents R**, **Kurita K**, **Holtas S**, **Svensson S**, **Eriksson L**, **Johansen C**. MR imaging of the temporomandibular joint: comparison of images of autopsy specimens made at 0.3 T and 1.5 T with anatomic cryosections. *Am J Roentgenol* 152: 1241–1244, 1989.

290   14. **Harrison DE**, **Harrison DD**, **Cailliet R**, **Janik TJ**, **Holland B**. Radiographic analysis of lumbar lordosis:
291   centroid, Cobb, TRALL, and Harrison posterior tangent methods. *Spine* 26: E235-242, 2001.

292   15. **Hay O**, **Dar G**, **Abbas J**, **Stein D**, **May H**, **Masharawi Y**, **Peled N**, **Hershkovitz I**. The Lumbar Lordosis
293   in Males and Females, Revisited. *PLOS ONE* 10: e0133685, 2015.

294   16. **Hirasawa Y**, **Bashir WA**, **Smith FW**, **Magnusson ML**, **Pope MH**, **Takahashi K**. Postural Changes of the
295   Dural Sac in the Lumbar Spines of Asymptomatic Individuals Using Positional Stand-Up Magnetic
296   Resonance Imaging: *Spine* 32: E136–E140, 2007.

297   17. **Hsieh PC**, **Koski TR**, **O'Shaughnessy BA**, **Sugrue P**, **Salehi S**, **Ondra S**, **Liu JC**. Anterior lumbar
298   interbody fusion in comparison with transforaminal lumbar interbody fusion: implications for the
299   restoration of foraminal height, local disc angle, lumbar lordosis, and sagittal balance. *J Neurosurg*
300   *Spine* 7: 379–386, 2007.

301   18. **Jinkins JR**, **Dworkin JS**, **Damadian RV**. Upright, weight-bearing, dynamic–kinetic MRI of the spine:
302   initial results. *Eur Radiol* 15: 1815–1825, 2005.

303   19. **J.R. Jinkins**, **J.S. Dworkin**, **C.A. Green**, **J.F. Greenhalgh**, **M. Gianni**, **M. Gelbien**, **R.B. Wolf**, **J.**
304   **Damadian**, **R.V. Damadian**. Upright, Weight-Bearing, Dynamic-Kinetic MRI of the Spine
305   pMRI/kMRI. *Riv Neuroradiol* 15: 333–357, 2002.

306   20. **Karadimas EJ**, **Siddiqui M**, **Smith FW**, **Wardlaw D**. Positional MRI Changes in Supine Versus Sitting
307   Postures in Patients With Degenerative Lumbar Spine. *Clin Spine Surg* 19: 495, 2006.

308   21. **Kimura S**, **Steinbach GC**, **Watenpaugh DE**, **Hargens AR**. Lumbar Spine Disc Height and Curvature
309   Responses to an Axial Load Generated by a Compression Device Compatible with Magnetic
310   Resonance Imaging. [Miscellaneous Article]. *Spine* 26: 2596–2600, 2001.

311   22. **Kulig K**, **Powers CM**, **Landel RF**, **Chen H**, **Fredericson M**, **Guillet M**, **Butts K**. Segmental lumbar
312   mobility in individuals with low back pain: in vivo assessment during manual and self-imposed
313   motion using dynamic MRI. *BMC Musculoskelet Disord* 8: 8, 2007.

314   23. **Lee ES**, **Ko CW**, **Suh SW**, **Kumar S**, **Kang IK**, **Yang JH**. The effect of age on sagittal plane profile of the
315   lumbar spine according to standing, supine, and various sitting positions. *J Orthop Surg* 9: 11, 2014.

316   24. **Levine D**, **Whittle MW**. The Effects of Pelvic Movement on Lumbar Lordosis in the Standing Position.
317   *J Orthop Sports Phys Ther* 24: 130–135, 1996.

318   25. **Lord MJ**, **Small JM**, **Dinsay JM**, **Watkins RG**. Lumbar lordosis: effects of sitting and standing. *Spine*
319   22: 2571–2574, 1997.

320   26. **Ludescher B**, **Effelsberg J**, **Martirosian P**, **Steidle G**, **Markert B**, **Claussen C**, **Schick F**. T2- and
321   diffusion-maps reveal diurnal changes of intervertebral disc composition: An in vivo MRI study at
322   1.5 Tesla. *J Magn Reson Imaging* 28: 252–257, 2008.

323   27. **Madsen R**, **Jensen TS**, **Pope M**, **Sørensen JS**, **Bendix T**. The Effect of Body Position and Axial Load on
324   Spinal Canal Morphology: An MRI Study of Central Spinal Stenosis. *Spine* 33: 61–67, 2008.

325   28. **Marshall PWM**, **Patel H**, **Callaghan JP**. Gluteus medius strength, endurance, and co-activation in the
326   development of low back pain during prolonged standing. *Hum Mov Sci* 30: 63–73, 2011.

327   29. **Mauch F**, **Jung C**, **Huth J**, **Bauer G**. Changes in the Lumbar Spine of Athletes From Supine to the
328   True-Standing Position in Magnetic Resonance Imaging: *Spine* 35: 1002–1007, 2010.

329   30. **McGraw KO**, **Wong SP**. Forming inferences about some intraclass correlation coefficients. *Psychol*
330   *Methods* 1: 30–46, 1996.

331   31. **NACHEMSON AL**. Disc Pressure Measurements. [Online]. *Spine* 6, 1981.
332   http://journals.lww.com/spinejournal/Fulltext/1981/01000/Disc_Pressure_Measurements_.20.asp
333   x.

334   32. **Naserkhaki S**, **Jaremko JL**, **Adeeb S**, **El-Rich M**. On the load-sharing along the ligamentous
335   lumbosacral spine in flexed and extended postures: Finite element study. *J Biomech* 49: 974–982,
336   2016.

337   33. **Nelson-Wong E**, **Callaghan JP**. Transient Low Back Pain Development During Standing Predicts
338   Future Clinical Low Back Pain in Previously Asymptomatic Individuals. *Spine* 39: E379, 2014.

339   34. **Nelson-Wong E**, **Gregory DE**, **Winter DA**, **Callaghan JP**. Gluteus medius muscle activation patterns
340   as a predictor of low back pain during standing. *Clin Biomech* 23: 545–553, 2008.

341   35. **Rea W**, **Kapur S**, **Mutagi H**. Intervertebral disc as a source of pain. *Contin Educ Anaesth Crit Care*
342   *Pain* 12: 279–282, 2012.

343   36. **Rodríguez-Soto AE**, **Berry DB**, **Palombo L**, **Valaik E**, **Kelly KR**, **Ward SR**. Effect of Load Magnitude and
344   Distribution on Lumbar Spine Posture in Active-duty Marines: *SPINE* 42: 345–351, 2017.

345   37. **Rodríguez-Soto AE**, **Jaworski R**, **Jensen A**, **Niederberger B**, **Hargens AR**, **Frank LR**, **Kelly KR**, **Ward**
346   **SR**. Effect of Load Carriage on Lumbar Spine Kinematics: *Spine* 38: E783–E791, 2013.

347   38. **Rosset A**, **Spadola L**, **Ratib O**. OsiriX: An Open-Source Software for Navigating in Multidimensional
348   DICOM Images. *J Digit Imaging* 17: 205–216, 2004.

349   39. **de Schepper EIT**, **Damen J**, **van Meurs JBJ**, **Ginai AZ**, **Popham M**, **Hofman A**, **Koes BW**, **Bierma-**
350   **Zeinstra SM**. The Association Between Lumbar Disc Degeneration and Low Back Pain: The
351   Influence of Age, Gender, and Individual Radiographic Features. *Spine* 35: 531–536, 2010.

352   40. **Sorensen CJ**, **Norton BJ**, **Callaghan JP**, **Hwang C-T**, **Van Dillen LR**. Is lumbar lordosis related to low
353   back pain development during prolonged standing? *Man Ther* 20: 553–557, 2015.

354   41. **Stefanakis M**, **Luo J**, **Pollintine P**, **Dolan P**, **Adams MA**. ISSLS Prize Winner: Mechanical Influences in
355   Progressive Intervertebral Disc Degeneration. *Spine* 39: 1365–1372, 2014.

356   42. **Tarantino U**, **Fanucci E**, **Iundusi R**, **Celi M**, **Altobelli S**, **Gasbarra E**, **Simonetti G**, **Manenti G**. Lumbar
357   spine MRI in upright position for diagnosing acute and chronic low back pain: statistical analysis of
358   morphological changes. *J Orthop Traumatol* 14: 15–22, 2013.

359   43. **Wang S**, **Xia Q**, **Passias P**, **Wood K**, **Li G**. Measurement of geometric deformation of lumbar
360   intervertebral discs under in-vivo weightbearing condition. *J Biomech* 42: 705–711, 2009.

361   44. **Wessberg P**, **Danielson BI**, **Willén J**. Comparison of Cobb Angles in Idiopathic Scoliosis on Standing
362   Radiographs and Supine Axially Loaded MRI: *Spine* 31: 3039–3044, 2006.

363   45. **Wilke H-J**, **Rohlmann F**, **Neidlinger-Wilke C**, **Werner K**, **Claes L**, **Kettler A**. Validity and interobserver
364   agreement of a new radiographic grading system for intervertebral disc degeneration: Part I.
365   Lumbar spine. *Eur Spine J* 15: 720–730, 2006.

366   46. **Wood KB**, **Kos P**, **Schendel M**, **Persson K**. Effect of Patient Position on the Sagittal-Plane Profile of
367   the Thoracolumbar Spine. *J Spinal Disord* 9: 165–169, 1996.

368   47. **Youdas JW**, **Garrett TR**, **Harmsen S**, **Suman VJ**, **Carey JR**. Lumbar lordosis and pelvic inclination of
369   asymptomatic adults. *Phys Ther* 76: 1066–1081, 1996.

370   48. **Yukawa Y**, **Kato F**, **Suda K**, **Yamagata M**, **Ueta T**, **Yoshida M**. Normative data for parameters of
371   sagittal spinal alignment in healthy subjects: an analysis of gender specific differences and changes
372   with aging in 626 asymptomatic individuals. *Eur Spine J* 27: 426–432, 2018.

373   49. **Zou J**, **Yang H**, **Miyazaki M**, **Wei F**, **Hong SW**, **Yoon SH**, **Morishita Y**, **Wang JC**. Missed Lumbar Disc
374   Herniations Diagnosed With Kinetic Magnetic Resonance Imaging. *Spine* 33: E140, 2008.

375

376   Table 1: Characteristics of the participants presented as the mean ± standard deviation. Age ($p = 0.81$) and
377   BMI ($p = 0.35$) are not statistically significant between sexes.

	Male (19)	**Female (21)**
Age (y)	24.7±3.5	24.9±2.1
Height (cm)	179.2±7.4	164.6±7.8
Weight (kg)	73.3±9.0	60.4±5.2
BMI (kg/m^2)	23.0±2.4	22.3±1.9

378

379
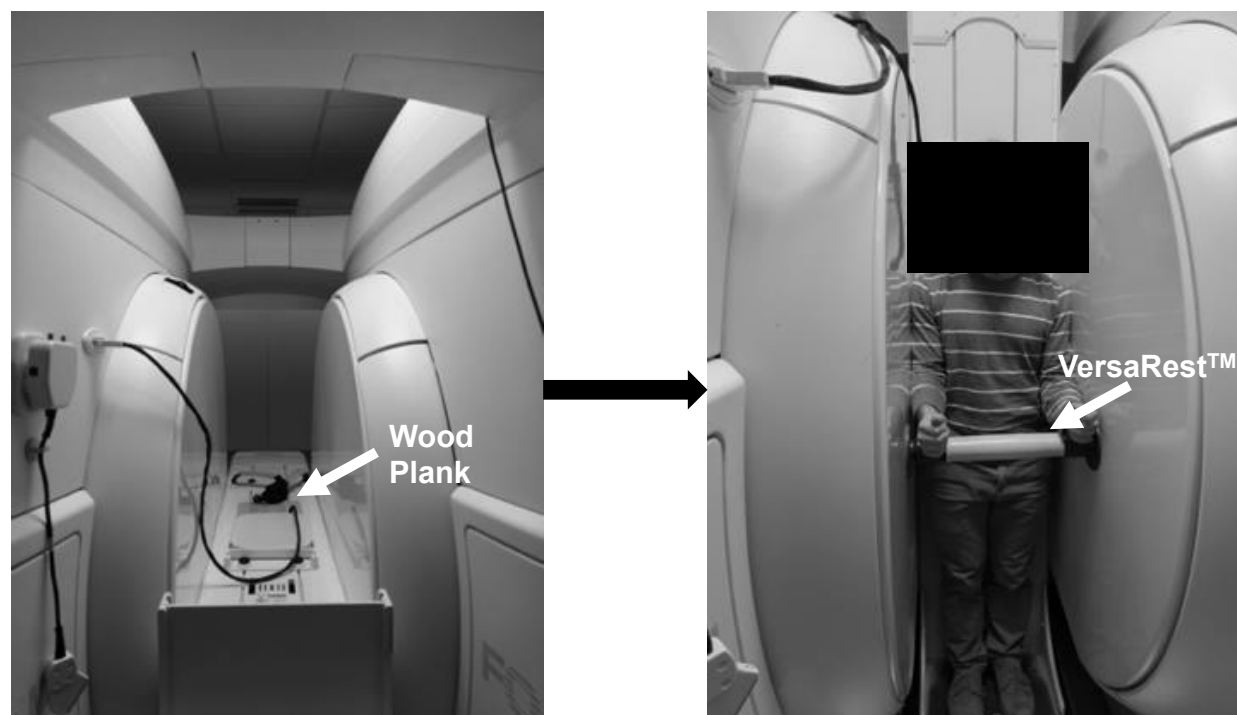
380
381 Figure 1: The pMRI with the table in supine (left) and standing (right) configurations. A wood plank placed
382 behind the participant to provide a continuous flat surface for the lumbar spine and is indicated by the white
383 arrow in the left panel. A VersaRest™ device to support the arms is indicated by the white arrow in the
384 right panel of the figure.
385
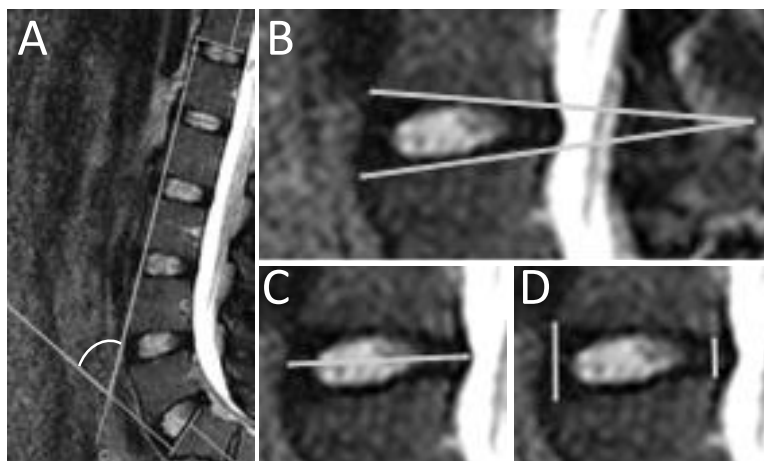
386
387 Figure 2: A representative image of the measurements in this study: A) The four-line Cobb angle, with the
388 white arc indicating the angle of measurement, quantifies the regional spinal alignment. Larger Cobb angles
389 reflect more lumbar lordosis. B) The segmental Cobb angle describes the "wedging" of the IVD. C) The
390 anterior to posterior height (A/P) ratio quantifies the relative change of shape of the IVD. D) The IVD
391 width quantifies the radial bulging that occurs in the IVD. All images are aligned in the same orientation
392 with the left being the anterior side.
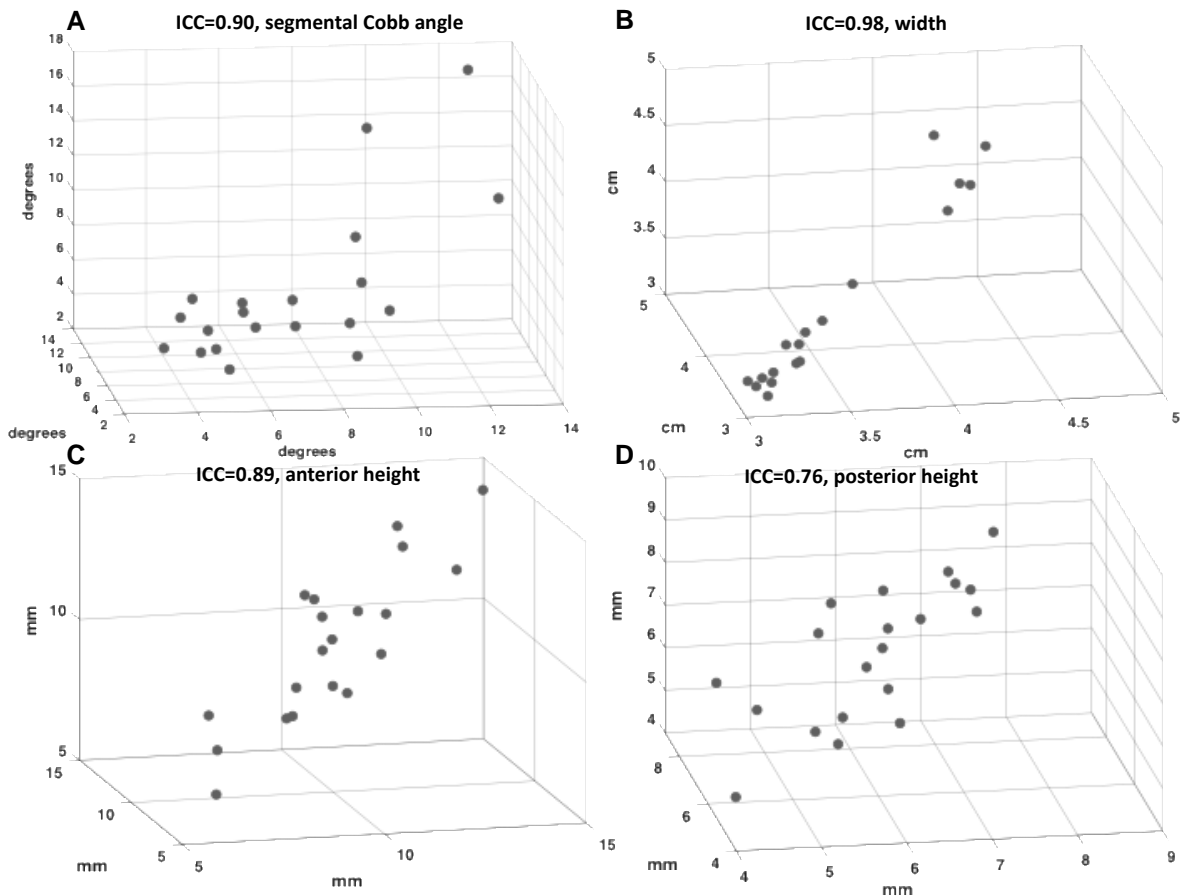
393
394　Figure 3: The intra-observer ICC values are shown for each measurement for individual IVD levels for A)
395　segmental Cobb angle, B) IVD width, C) anterior height, and D) posterior height. Each axis represents an
396　independent observer trial for the measurement. A written rubric for measurement based on anatomical
397　landmarks (segmental Cobb angle, IVD width, the anterior-, and posterior- heights) was used. The intra-
398　observer analysis was performed using measured variables obtained on three different nonconsecutive days.
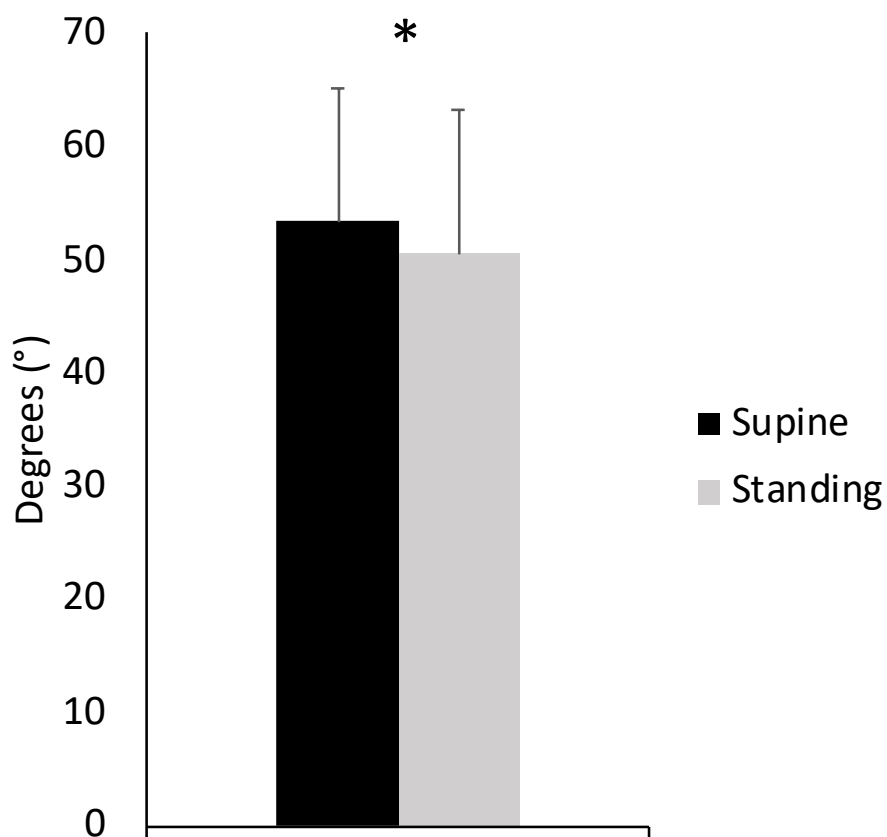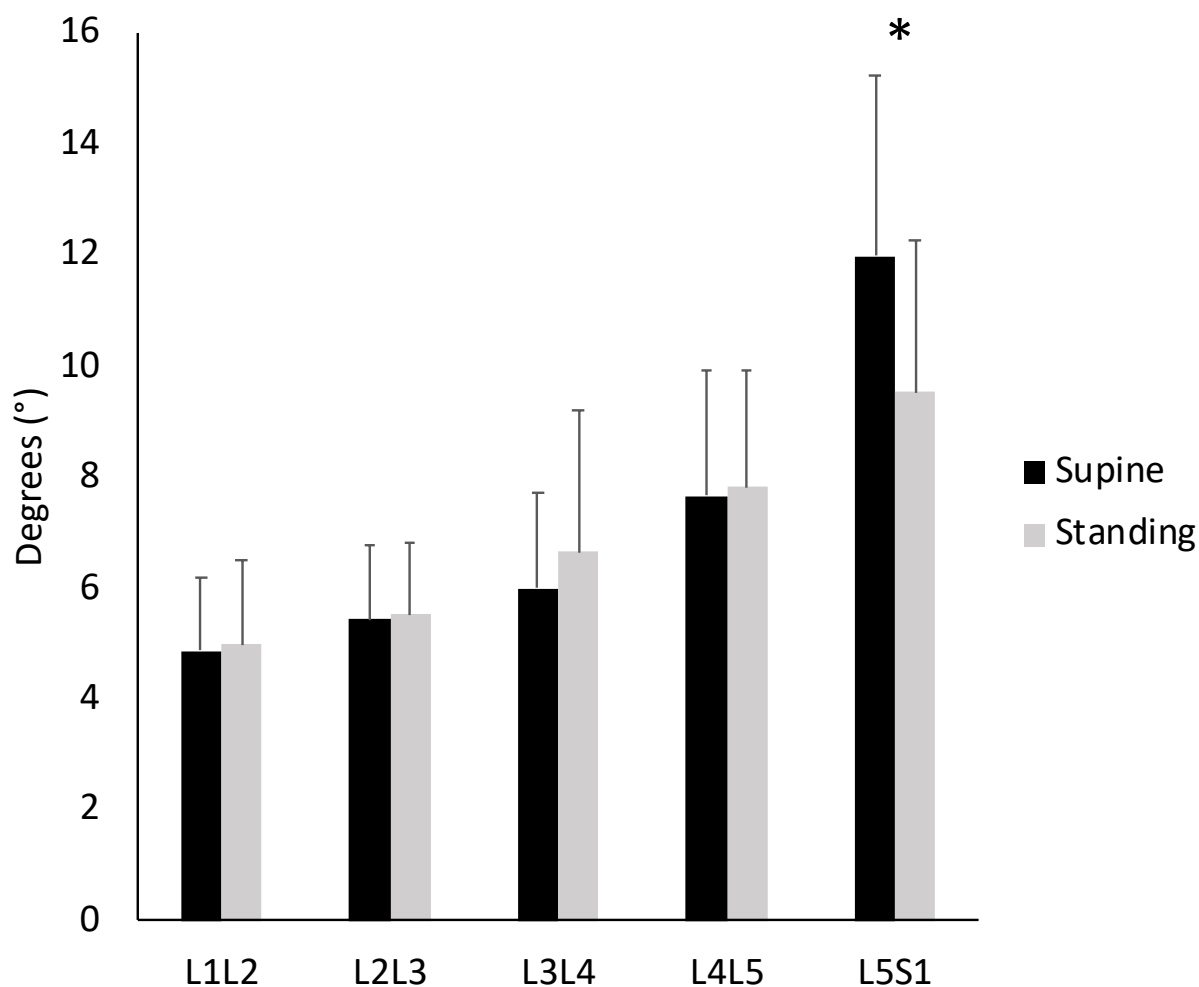
399
400 Figure 4: The Cobb angle for all participants in each position show that lordosis decreases in standing (*
401 :two-way repeated measures ANOVA, $p < 0.05$). Error bars indicate standard deviations.

402 Table 2: P-values for the three-way repeated measures ANOVA examining the effects of sex, level, and
403 position and their interactions on the segmental Cobb angle, A/P ratio, and IVD width measurements.

|	*p*-value		
Factors	**Segmental Cobb angle**	**A/P ratio**	**IVD width**
Sex	0.027	< 0.001	< 0.001
Level	0.004	< 0.001	< 0.001
Position	---	< 0.001	< 0.001
Sex*Level	---	---	---
Sex*Position	---	---	---
Level*Position	< 0.001	< 0.001	< 0.001
Sex*Level*Position	---	---	---

404

405
406 Figure 5: The mean segmental Cobb angles at each lumbar level for all participants in supine and in
407 standing. The segmental Cobb angle decreased at L5/S1 in standing (* :three-way repeated measures
408 ANOVA, $p<0.05$). Error bars indicate standard deviations.
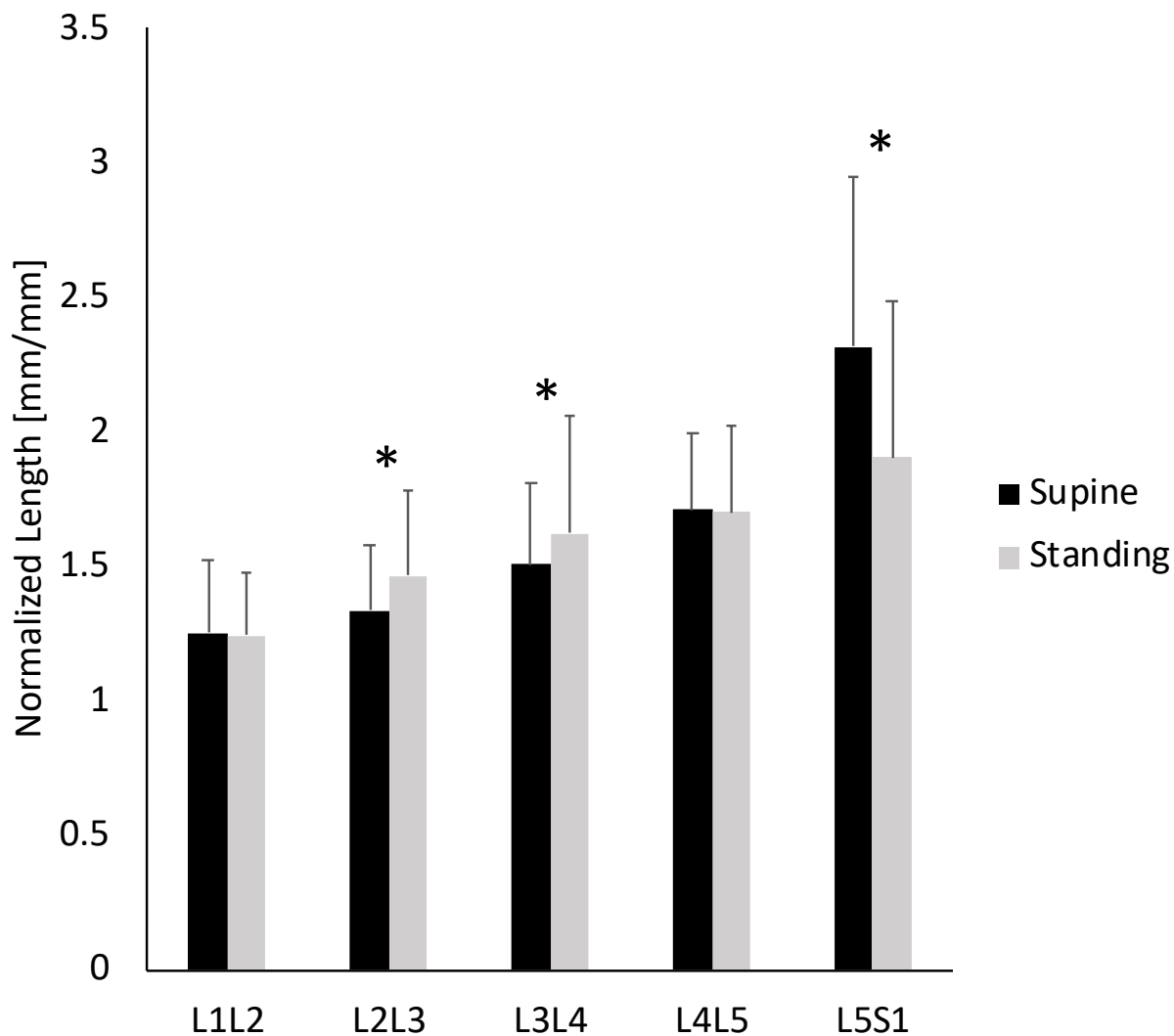
409
410   Figure 6: The A/P ratios show that L2/L3 and L3/L4 increases in standing, and decreased in the L5/S1.
411   (*: three-way repeated measures ANOVA, $p < 0.05$). Error bars indicate standard deviations.
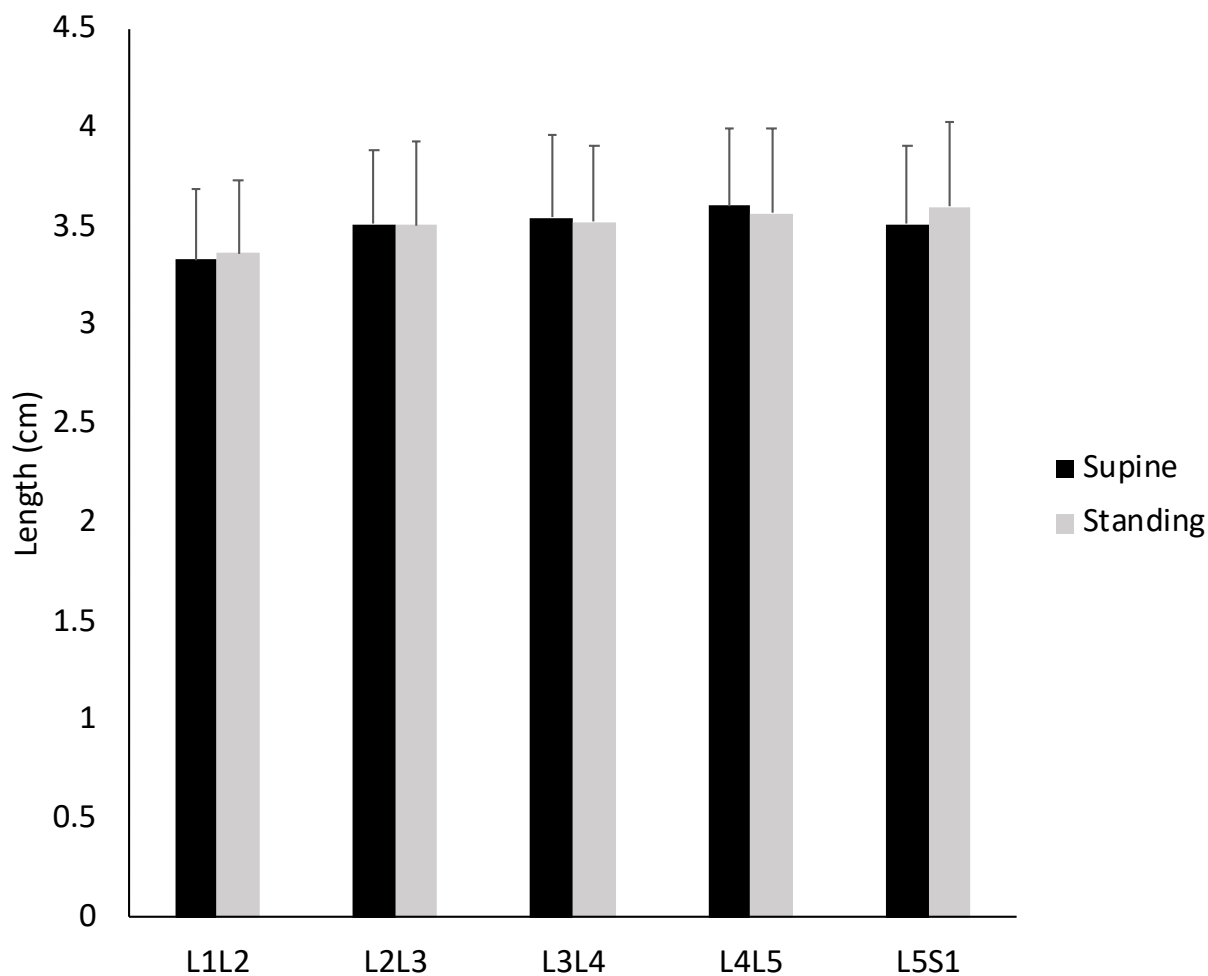
412
413   Figure 7: The IVD width shows no differences at all levels between supine and standing positions across
414   participants. Error bars indicate positive standard deviations.