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Cervical canal morphology : effects of neck flexion in normal condition
- New elements for biomechanical simulations and surgical
management -

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Abstract (Max 300 words)

Study Design. Continuous measurements and computation of absolute metrics of cervical subarachnoid space (CSS) and spinal cord (SC) geometries proposed are based on *in vivo* magnetic resonance imaging and 3D reconstruction.

Objective. The aim of the study is to offer a new methodology to continuously characterize and to quantify the detailed morphology of the CSS and the cervical SC in 3D for healthy subjects in both neutral supine and flexion.

Summary of Background Data. To the best of our knowledge, no study provide a morphological quantification by absolute indices based on the 3D reconstruction of SC and CSS thanks to *in vivo* magnetic resonance imaging. Moreover, no study provide a continuous description of the geometries.

Methods. Absolute indices of SC (cross-sectional area, compression ratio, position in the canal, length) and of CSS (cross-sectional area, occupational ratio, lengths) were computed by measures from 3D semi-automatic reconstructions of high resolution *in vivo* magnetic resonance images (3D T2-SPACE sequence) on healthy subjects (N=11) for two postures : supine neutral and flexion neck positions. The variability induced by the semi-automatic reconstruction and by the landmarks positioning were investigated by preliminary sensitivity analyses. Inter and intra-variability were also quantified on a randomly chosen part of our population (N=5).

Results. The length and cross-sectional area of SC are significantly different ($p<0.05$) in flexion compared to neutral neck position. Spinal cord stays centered in the canal for both postures. However, the cross-sectional area of CSS is submitted to low variation after C3 vertebra for both postures. OR and CR after C3 are significantly lower in flexion.

Conclusions. This study presented interpretations of morphological measures :

1) left-right stability (described by the Left-Right eccentricity index) ensured by the denticulate ligaments and the nerve roots attached to the dural sheaths, 2) a Poisson effect of the SC was partially notified through its axial (AP diameter, OR, CR) and its longitudinal geometrical descriptions (LSC). Such

morphological data can be useful for geometrical finite element modeling and could now be used to compare with injured or symptomatic subjects.

Key points. (3-5 full sentences of the main pts of the article)

- The mechanical roles of the structures inside the vertebral canal in flexion : left-right stability (described by the LR eccentricity index) ensured by the denticulate ligaments and the nerve roots attached to the dural sheaths.
- A Poisson effect of the SC was partially highlighted through its axial (AP diameter, OR, CR) and its longitudinal geometrical descriptions (LSC).
- Such morphological data can be useful for geometrical finite element modeling of the canal in terms of boundaries, initial conditions as well as for an optimization of the mechanical properties by geometrical calibration of the model.

Précis. (Submit a short description of the manuscript to appear in the Table of Contents, 3 sentences
Max **50 words.**)

The aim of the study is to offer a new methodology quantifying continuously the detailed morphologies of the cervical subarachnoid space and the spinal cord for healthy subjects in both neutral supine and flexion. *In vivo* magnetic resonance imaging and 3D semi-automatic reconstruction provide through computation of absolute metrics for both geometries.

1 **1. Introduction**

2 Magnetic Resonance Imaging (MRI) has become a gold standard method to understand different
3 physiological mechanisms of the spine. In the context of degenerative process, Kinematic MRI (kMRI), or postural
4 MRI, which refers to imaging of the spine at different neck positions, is largely used to diagnosis position-
5 dependent alterations that could not be detected in normal posture. It is mostly applied qualitatively to visualize
6 cervical canal narrowing or spinal impingement by degenerated disk in flexion for instance, however little is
7 known concerning the dynamical changes occurring at the level of the healthy cervical subarachnoid space(CSS)
8 and spinal cord (SC) tissues.

9 Considering the limited spatial resolution that could be reached on conventional MR system (1.5 or 3T),
10 the subarachnoid space is often simplified as a dural tube or as a space in the sagittal plane between the spinal
11 cord and the anterior and posterior parts of the canal. Using this assumption, Kato et al. provided a large data
12 base of MRI morphological measurements and showed the influence of the age and the gender on the occupation
13 rate of the spinal cord in the dural tube on a large population⁵. Dahlan *et al.*⁶ established normal values of
14 cervical canal diameters for young military subjects. Others studies focused on the SC location in the cervical
15 canal based on two-dimensional (2D) visualization analysis for healthy subjects⁷ and for symptomatic subjects⁸.
16 CSS and SC characterization at specific spine levels (mid-vertebrae, discs) can also be found, with different
17 parameters such as compression ratio, cross-sectional area and spinal cord displacement that have been used in
18 clinical research context^{1,2,3,4}. In patients with Cervical Spondylotic Myelopathy (CSM), area of the SC, as well as
19 antero-posterior and left-right diameters were described^{13,14} so as to evaluate the cord compression in the canal.

20 When characterizing changes in posture, some articles considered a quantification of the strain of cord
21 while others considered displacement measurements. Indeed, longitudinal strain of human cervical cord can
22 reach a magnitude of 5% and 20% for, respectively, flexion and extension^{9,10,11,12}, respectively.

23 In this study, based on 3D MR acquisitions in healthy subjects in both neutral supine and flexion, we propose
24 a new methodology to characterize and to quantify the morphology of the CSS and the cervical SC in 3D for
25 healthy subjects in both neutral supine and flexion. This approach aims at providing accurate and detailed
26 morphological data (cross-sectional area, eccentricity indices, and displacements of the cord and canal) in order
27 to have a deeper understanding of the impact of the flexion in the cervical canal.

28 **2. Method**

29 **MRI acquisition**

30
31 Eleven european healthy subjects (5 females and 6 males, mean age : 30 +/- 6y, BMI : 23.86 +/- 1.78
32 kg/m²) were scanned using a 3T MR system (Siemens Healthineers, Erlangen, France) equipped with head,
33 neck and spine coils. Subjects were first examined with the neck in neutral and flexion positions, using a
34 dedicated homemade device (device flexion up to 40°). Images were acquired using a sagittal 3D T₂-SPACE
35 sequence (Sampling Perfection with Application optimized Contrasts using different flip angle Evolution)
36 with the following parameters: voxel size (1x1x1 mm³), field-of-view (256x256 mm²), echo time (TE : 124
37 ms), repetition time (TR : 1500 ms,) , total acquisition time (6 min). The MR protocol was approved by the
38 institutional ethics committee and all subjects signed the informed consents. The cohort was chosen
39 excluding history, presence of cervical pathologies or deformations.

40 **Segmentation and anatomical markers**

41 The SC was first segmented in 3D by a semi-automatic approach using the Spinal Cord Toolbox (SCT,
42 3.1.1)¹⁵ and providing SC centerline. The outer canal border, assumed as the dura mater, was then
43 segmented by a semi-automatic approach from ITK-SNAP software¹⁶. The 3D CSS was defined as the space
44 between the 3D canal segmentation and the 3D SC segmentation [Fig. 1-a,b].

45 Eleven landmarks [Fig. 1-b] were selected, by one operator on the middle slice of the sagittal view, using 3D
46 Slicer 4.8.1¹⁷ for the delimitation of the segment of interest:

- 47 1) "*Reference landmarks*": at the top of the dens of C2 (axis) and at the posterior extremity of C7 inferior
48 endplate;
- 49 2) "*Cervical vertebral landmarks*", at the posterior extremities of each endplate (superior and inferior, C2 to
50 C6).

51 **Data preparation, indices and lengths computation**

52 The post-processing steps performed using in-house Matlab codes (R2018a version,
53 Matlab®MathWorks,1984) are summarized in [Fig. 1] and were performed for both neutral and flexion
54 positions.

55 Both 3D segmentations (dural tube and SC raw surface meshes) were smoothed using ($\lambda : 1, \sigma : 0$)¹⁸.

56 Morphological parameters were computed from anatomical markers and centerline coordinates in less than
 1 10 s per subject (Dell Latitude 7480, Intel® Core™ i7-7600U CPU – 2.80GHz/2.90GHz, RAM : 8Go).
 2 57
 3
 4 58 The boundaries of the SC and the canal were interpolated as the intersection¹⁹ of the surface meshes and
 5
 6 59 meshed planes orthogonal to the centerline [Fig. 2-c] using 3D splines. Then, the CSA of the SC, canal and
 7
 8 60 CSS (CSA_{SC} , CSA_{canal} , CSA_{CSS} , respectively) were computed (see [1]).

10 61 The cord transverse and antero-posterior diameters ($\emptyset T_{SC}$, $\emptyset AP_{SC}$ respectively), as well as distance
 11
 12 62 between the SC and the canal in anterior (A), posterior (P), right (R) and left (L) directions were computed
 13
 14 63 from the most eccentrical points in AP (4) and LR (5) directions. Compression (CR - 2) and occupation (OR –
 15
 16 64 3) ratios, as well as eccentricity indices were then derived from these metrics⁷ (see [2] to [5]).

$$65 \quad CSA_{CSS} = CSA_{canal} - CSA_{SC} \quad (1)$$

$$66 \quad CR = \frac{\emptyset AP_{SC}}{\emptyset T_{SC}} \quad (2)$$

$$67 \quad OR = \frac{CSA_{SC}}{CSA_{canal}} \quad (3)$$

$$68 \quad AP_{eccentricity} = \left(\frac{P-A}{P+A} \right) * 100 \quad (4)$$

$$69 \quad LR_{eccentricity} = \left(\frac{L-R}{L+R} \right) * 100 \quad (5)$$

70 An $AP_{eccentricity} > 0$ (<0) indicates that the SC is anteriorly (posteriorly) positioned.

71 Similarly, a $LR_{eccentricity} > 0$ (<0) indicates that the SC is located on the right (left) side of the canal.

72 Three specific lengths were also computed in both positions^{20, 21}: the length of the cervical spinal cord
 73 (LSC), length of the cervical spinal anterior column (LAC) and length of the cervical spinal posterior column
 74 (LPC). They were respectively delimited by the caudal side of the pons to C7 inferior endplate, the C2 dens
 75 process to C7 inferior endplate, and the top of C1 posterior arch to C7 inferior endplate. Three 3D splines
 76 passing through the points positioned manually by an operator to define each curvature were computed to
 77 get more accurate lengths.

78 **Inter-operator variability, intra-operator variability and statistical analyses process**

79 The comparison between CSA_{canal} measurements derived from ITK SNAP and manual segmentation

was provided in 5 subjects randomly selected [Tab. 1] to assess the accuracy of the semi-automatic segmentation. Additional information on the reliability of the SC segmentation and CSA_{SC} can be found in literature¹⁵. Inter- (by 2 raters) and intra-operator (at 2 different time points -operator 1) variabilities of 3D reconstruction and landmarks positioning were also assessed reporting the Euclidian distance, mean relative error of the CSA (CSS, SC) and of the eccentricity indices (AP, LR) [Tab. 2].

Three metric values were calculated at each vertebral level : spatial averaged value (over the whole vertebra) (AVD VERT), spatial value for a cross-sectional plane mid-vertebra (MID-VERT) and spatial value for cross-sectional plane located at the middle of the intervertebral disc (MID-IVD) (vertebral levels defined as the “cervical vertebral landmarks” projected onto the centerline). For both postures (neutral and flexion), all values are reported as averaged value with standard deviation by vertebra and disc on all subjects. Mean vertebral level positions across all subjects were computed from : the position of each vertebra according to the “Reference landmarks” and “Cervical vertebral points” positions projected to the centerline. Statistical comparisons between neutral and flexion measurements were performed using RStudio (© 2009-2018 RStudio, Inc. – Version 1.1.463). Due to the small number of samples, paired samples Wilcoxon tests (non-parametric test) were used. Significant differences were defined for p-values < 0.05 (noted * in the summary results table [Tab. 4]).

3. Results

Segmentation and inter-operator reliability

The maximum error value between manual and automatic canal CSA measurements was found for the C2 dens reaching 25.06% while for the others cervical levels, the canal CSA relative errors reminded lower than 18%. The standard deviation was steady around 15% [Tab. 5 - Supplemental Digital Content].

The maximal distance, when considering inter-operator differences, was found of 2.29 mm (corresponding to an error of two 1 mm-isotropic voxels) in neutral position and 4.29 mm (ie. 4 voxels) in neutral position and 3.62 mm (ie. 4 voxels) in flexion.

Consequences of inter/intra-operator differences in landmarks positioning were additionally assessed on four metrics (CSA_{SC} , CSA_{CSS} , $AP_{eccentricity}$ and $LR_{eccentricity}$). The first tenth of the cervical segment (C1-C2 functional unit) presented high variability (gray zone [Tab. 1]), whereas mean differences were less than 5% of the measured values otherwise, except for the CSA_{CSS} (inter-operator mean relative error of 7.5%).

108 **Cervical subarachnoid space (CSS) and spinal cord (SC) in the canal**

109 Cross-sectional areas and occupational ratio

110 The mean CSA_{CSS} evolution along the canal after normalization in abscissa is depicted [Fig. 2]. The
111 abscissa represents the averaged distances of each “*cervical vertebral landmarks*” from the top “reference
112 landmarks” for all the subjects normalized using :

$$114 \quad Y = \frac{X - \min(X)}{\max(X) - \min(X)}, \quad (6)$$

115
116 with Y : the normalized vector of the abscissa.

117 X : the vector of mean values of the distances on the centerline from the top projected “*reference*
118 *landmark*” to the projected “*cervical vertebral landmark*”.

119
120 CSA rapidly decreased from C2 dens to C2 inferior endplate (from 481.6 mm² to 177.5 mm² in neutral
121 position ; 379.8 mm² to 157.9 mm² in flexion), with minimal values around C3, followed by a low increasing
122 and oscillating phase to reach 157 mm² in neutral and 164 mm² in flexion. CSA differences between both
123 postures were found significant ($p < 0.05$) for C1-C2, C5, C6, C7 described in (cf. [Tab. 4]).

124 The mean of CSA_{SC} for both postures is given on [Fig. 5]. In flexion, it was systematically lower than in
125 neutral position and differences were found significant ($p < 0.05$) for all local locations (see [Tab. 4]).

126 The mean OR increased from C2 dens to C2 inferior endplate for the both neutral and flexion postures
127 (from 0.18 to 0.32 and 0.19 to 0.32, respectively). After the superior C3 endplate (0.33 – neutral ; 0.35 –
128 flexion), the flexion OR decreases faster than in neutral position with an oscillating behavior until the C7
129 inferior vertebrate endplate (0.31 – neutral ; 0.22 - flexion). Large standard deviations could be noticed (± 8 -
130 30% - neutral ; ± 13 -45% - flexion) [Fig. 2]. OR differences between both postures were found significant
131 ($p < 0.05$) for C1-C2, C5, C6, C7 described in (cf. [Tab. 4 - Supplemental Digital Content]).

132 Eccentricity indices and compression ratio

133 The mean AP and LR eccentricity indices, as well as the CR index along the normalized length of the canal
134 are depicted [Fig. 3]. The first tenth of the presented curves (0 to 0.1 in abscissa) will not be considered in

135 further analysis because of the difficulty of the post-processing algorithm (section 2.3) to be efficient with
136 the small complex geometry of the subarachnoid space (*cisterna magna/pontis/interpeduncularis, medulla*
137 *oblongata*) between the foramen magnum and the C2 dens.

138 Between the C2 dens and the inferior C2 endplate, the $AP_{eccentricity}$ index decreased steadily with the
139 same behavior for both neutral and flexion postures (from 52% to -22% and 58% to -24%, respectively). After
140 the C3 superior endplate, mean $AP_{eccentricity}$ index in neutral was systematically lower than in flexion
141 position. [Fig. 3-Top]. Differences between both postures were found significant ($p < 0.05$) for C1-C2, C5, C6,
142 C7 described in (cf. [Tab. 4]).

143 The $LR_{eccentricity}$ index constantly oscillated around 0% and 8% respectively in neutral and flexion neck
144 postures respectively [Fig.3-Middle]. No significant difference in $LR_{eccentricity}$ index between the postures
145 was found ($0.08 < p < 0.97$) except for the vertebral level C1-C2 (cf. [Tab. 04]).

146 The CR index decreased steadily between C2 dens and to C7 inferior endplate for both posture. The CR
147 for the flexion case was systematically lower than in neutral position, except along the C3 vertebra [Fig. 3-
148 Bottom]. CR differences between neutral and flexion neck postures were significant ($p < 0.05$) locally for the
149 vertebral levels C4, C5, C6 and for the mid-levels of intervertebral discs values of C4/C5 to C6/C7 [Tab. 04].

150 Anterior/Posterior columns and of the spinal cord

151 The mean length values were measured equal to 118 ± 5 mm and 120.3 ± 7.6 mm for LAC, 107 ± 6 and
152 120.4 ± 6.4 mm for LPC, 142 ± 7 mm and 159.4 ± 11.5 mm for LSC in neutral and flexion neck postures,
153 respectively, with significant differences between both the postures in each case ($p < 0.05$) [Fig. 4, Tab. 4].

154 4. Discussion

155 This study proposes a new approach to collect detailed anatomical measurements of the cervical canal.
156 Using MRI segmented 3D geometrical reconstructions, it was possible to investigate the morphological
157 changes between neutral supine and neck-flexion positions. Different geometrical metrics (CSA, eccentricity
158 indices, ratios) related to the SC and the CSS could be derived. The most noticeable results are summarized
159 in [Tab. 3].

160 Cord and CSS kinematical description

161 Firstly, the low oscillating behavior of CSA_{CSS} and OR indices along the spinal segment in [Fig. 2,3]
162 describes the geometry of dura mater at each spine level : nerve root funnel-shaped lateral extensions of

163 sheaths leave the dura mater as spinal ganglions toward the peripheral nervous system²², hence including
164 pseudo-periodic fluctuations in the CSS outer border.

165 Secondly, the kinematic of the cord is not only induced by the flexion itself but also by the surrounding
166 structures. The spinal cord being fixed to the superior anatomical structures (pons, *medulla*) on one hand
167 and to the *filum terminale* on the other hand, it is subject to tensile forces applied in both cranio-caudal and
168 antero-posterior directions when flexed. Previous studies reported up to 2-mm displacements of the
169 *medulla oblongata* and the pons in flexion²³. Here a “stretching” phenomenon (+13% for LSC in flexion with
170 respect to neutral position, after C2 endplate) occurs while the SC is pull through the anterior side of the
171 spine column, as reflected by the $AP_{eccentricity}$ and $LR_{eccentricity}$ [Fig 3-a,b]. The nerve roots attached in the
172 dural sheaths could be limiting the longitudinal motion and allow an elongation that follows the spinal
173 motion. The SC lateral position stays globally centered (slight shift on the left : 2-3% from the center of the
174 canal), in line with the literature⁷, and similar in neutral and in flexion. Indeed, both denticulate ligaments²⁴,
175 ²⁵ between the arachnoid (assumed to be stick to the dura mater) and the pia mater, and nerve roots leaving
176 the SC dorsal and ventral side by pairs and exiting the CSS by the dural sheath, insure coronal stabilization
177 of the SC.

178 Thirdly, the high reduction of CSA_{CSS} from C2 dens to C3 vertebra in flexion position compared to the
179 neutral one appears to be induced by the high mobility of the upper cervical segment²⁶. After the C3
180 vertebra, the CSA_{SC} was globally steady while the CSA_{CSS} decreased. In addition, the action of the yellow
181 and posterior longitudinal ligaments inside the vertebral should be noticed²⁷ while explaining the CSS
182 modification²⁸.

183 **Toward cord and spine biomechanical description**

184 The geometrical evolution described by the CR index was intrinsically linked to the mechanical
185 properties of the spinal cord. Indeed, the decrease of the CR from C4 to C6 observed in flexion depicts a
186 significant strain of the SC from 3% to 7%. Such results underline the “stretching” phenomenon previously
187 mentioned. This is further confirmed by the 13% increase of the LSC in flexion, in line with literature^{10,29, 21,9}.
188 The “stretching” phenomenon results from the the Poisson effect described as the amount of lateral
189 contraction against the amount of axial elongation experienced by a material under the action of a force.
190 The three OR, CP, and LSC metrics could overcome the current lack of mechanical characterization and could
191 be used for biomechanical modeling validation. Such Poisson effect can induce some local stresses or

192 damages in the structure near the zone where the cord is attached, namely nerve roots and denticulate
193 ligaments⁹.

194 The LAC and LPC values (respectively +2% and +12% in flexion) are also in line with literature²⁰
195 (respectively 5% and 8%). The LSC metric in comparison to LAC and LPC ones shows that the SC follows the
196 motion of the canal in freeing more space posteriorly in flexion ($-22\% < AP_{eccentricity} < 47\%$) than in neutral
197 position ($-22\% < AP_{eccentricity} < 7\%$) after C2 vertebra. Validation and further use of spine models, especially
198 with finite element modeling, require advanced knowledge of spinal cord interaction with surrounding
199 structures. Hence the data related to the location of the cord and its space distribution obtained in this study
200 could provide a strong added value for model design. In addition, spinal cord positioning and length
201 variations are also providing additional indirect information (based on Poisson ratio effects) to support
202 further modeling choices. Altogether, our study provide the necessary measurements [Tab. 4] in a healthy
203 adult population in physiologically conditions for such validation.

204 **Clinical aspects**

205 In this study, we presented ten morphological parameters were used to describe the postural
206 modifications occurring in the canal. These parameters were chosen in relation to their use in a clinical
207 research context. Indeed, transverse area criteria corresponding to our CSA_{SC} , CSA_{CSS} , CSA_{canal} ,
208 $\emptyset T_{SC}$, $\emptyset AP_{SC}$ and CR, are used for CSM description^{13,14}. CSM, disc herniation, osteophytes (bony outgrowth)
209 can also cause reduction of the canal and an occupation ratio (sagittal diameters ratio of spinal cord over
210 canal, or ratio of spinal cord over canal area corresponding to our OR index) could be useful to quantify the
211 degree of compression^{30,31}. Moreover, additional parameters related to the location of the spinal cord in the
212 canal ($AP_{eccentricity}$ and $LR_{eccentricity}$ indices) and the characteristic lengths (LSC, LAC, LPC) complete this
213 physiological database of healthy subjects that could now be used to compare with injured or symptomatic
214 subjects. This methodology and database open the perspective of more accurate clinical indices.

215 **Limitations**

216 The first limitation of our methodology is that the MR acquisitions were performed in supine position,
217 which is not a daily physiological posture. A previous study showed no significant difference of the spinal
218 cord length between erect and supine position²⁹. However, with cervical lordosis changes, a slight difference
219 between erect and supine position is expected for SC position in the CSS and eccentricity indices.

220 Nonetheless, as the cerebrospinal fluid mechanical properties are similar to water properties^{32, 33}
1
2 221 (incompressibility), the fluid limits the effect of gravity in supine position.

3
4 222 The second limitation is the ambiguous difference between displacements and elongation of the SC in
5
6 223 the CSS, which will be confirmed in the future by refine MR acquisition of head neck at 7T in order to enable
7
8 224 a more precise localization of the nerve roots along the CSS, in complement to description already provided
9
10 225 at 3T³⁴.

11
12 226 The last limitation of our methodological work is the small amount of subjects currently included and the
13
14 227 lack of symptomatic subjects. Future investigations and multicentric studies could complete this work to
15
16 228 turn it into normative database adapted to a clinical routine.

19 229 **5. Conclusion**

20
21
22
23 230 A new methodology allowing a detailed description of the vertebral canal morphology thanks to high
24
25 231 resolution 3T-kMRI was developed. It allowed characterizing the CSS dynamic behavior through 10
26
27 232 geometrical metrics. Reference values in healthy population are provided in [Tab. 4].

28
29 233 The mechanical roles of the different structures inside the vertebral canal in flexion were also confirmed
30
31 234 through geometric measurements changes : 1) left-right stability (described by the LR eccentricity index)
32
33 235 ensured by the denticulate ligaments and the nerve roots attached to the dural sheaths, 2) a Poisson effect
34
35 236 of the SC was partially notified through its axial (AP diameter, OR, CR) and its longitudinal geometrical
36
37 237 description (LSC). Such morphological data can be useful for geometrical finite element modeling of the
38
39 238 canal in terms of boundaries or initial conditions or for an optimization of the mechanical properties by
40
41 239 geometrical sensitivity analysis. Confronting this methodology and these results in a further study with a
42
43 240 pathological cohort (CSM, post-traumatic population) is crucial to refine these clinical criteria in the medico-
44
45 241 surgical management.

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Abbreviations.

AP : antero-posterior

AVD VERT : spatial averaged value (over the whole vertebra)

CP : compression ratio

CSA : cross-sectional area

CSM : cervical spondylotic myelopathy

CSS : cervical subarachnoïd space

LAC : length of anterior column

LPC : length of posterior column

LR : left-right

LSC : length of spinal cord

MID-IVD : spatial value for cross-sectional plane located at the middle of the intervertebral disc

MID-VERT : spatial value for a cross-sectional plane mid-vertebra

MRI : magnetic resonance imaging

kMRI : kinematic magnetic resonance imaging

OR : occupational ratio

SC : spinal cord

Intra-operator differences	CSA SC [mm²]	CSA CSS [mm²]	AP Eccentricity [%]	LR Eccentricity [%]
Neutral	1.36±0.85 ; 0/2.69	16.42±7.32 ; 0.01/29.98	3.13±2.02 ; 0/6.56	3.85±4.66 ; 0.01/18.18
	2.36±0.97 ; 0.5/4.57	2.26±2.17 ; 0.02/11.27	2.11±2.15 ; 0.01/10.08	2.15±2.03 ; 0.02/11.58
Flexion	3.49±1.79 ; 0/6.92	32.28±22.38 ; 0.06/72.69	6.62±3 ; 0.05/11.79	3.58±2.42 ; 0.12/8.98
	1.1±1.26 ; 0.01/11.35	4.81±4.56 ; 0.03/24.68	3.54±3.11 ; 0.03/15.13	2.93±2.78 ; 0.01/14.53

Table 1

	Inter-operator		Intra-operator	
	Neutral	Flexion	Neutral	Flexion
C1 odontoid (ref pt)	1.72 ; 0.52/4.26	4.29 ; 1.47/6.19	2.12 ; 0.56/4.02	3.62 ; 2.36/6.22
C2 inf	2.03 ; 0.31/3.51	6.4 ; 1.27/29.75	1.44 ; 0.36/3.2	2.64 ; 1.13/6.09
C3 sup	2.29 ; 1.13/3.82	2.37 ; 0.37/3.37	1.53 ; 0.87/3.83	2.51 ; 0.86/5.67
C3 inf	2.05 ; 0.98/4.07	2.61 ; 1.33/4.87	2.02 ; 1/3.61	2.49 ; 1.01/5.58
C4 sup	1.62 ; 0.27/3.01	2.77 ; 1.77/3.4	1.29 ; 0.42/2.37	2.65 ; 1.36/5.07
C4 inf	2.03 ; 0.36/3.73	2.61 ; 1.3/3.51	1.63 ; 0.32/2.53	2.6 ; 1.12/5.08
C5 sup	1.96 ; 0.74/3.52	3.69 ; 1.32/12.06	1.43 ; 0.72/2.77	2.43 ; 1.2/5.01
C5 inf	2.12 ; 0.89/4.25	2.99 ; 1.26/5.35	1.29 ; 0.08/2.57	2.85 ; 1.53/6.31
C6 sup	1.69 ; 0.9/2.73	3.84 ; 1.54/14.01	1.65 ; 1.03/2.4	2.44 ; 0.73/5.02
C6 inf	1.61 ; 0.4/3.43	2.84 ; 1.27/5.13	1.31 ; 0.29/2.5	2.49 ; 0.17/6.75
C7 sup	1.32 ; 0.38/2.39	3.76 ; 1.3/14.49	1.42 ; 0.5/2.62	2.19 ; 0.67/5.05
C7 inf (ref pt)	1.32 ; 0.11/2.72	2.51 ; 1.01/4.81	1.47 ; 0.71/2.28	2.43 ; 1.43/5.44

Table 2

Morphological parameters	Main position-dependent evolution
CSS CSA	Significant decrease from C1 to C3 superior endplate. From C3 to C7, low variation and oscillating phase around 157 mm ² in neutral and 162 mm ² in flexion positions.
SC CSA	Significantly lower in flexion than in neutral supine position.
OR	After the superior C3 endplate (0.33 – neutral ; 0.35 - flexion), the flexion OR decreases faster than in neutral position.
CR	The CR index decreased steadily between C2 dens and to C7 inferior endplate for both posture. The CR for the flexion case is systematically lower.
AP eccentricity index	Same location for the both postures before C3 vertebra. After C3, in flexion the SC is more anteriorly positioned with respect to the center of the canal.
LR eccentricity index	Spinal cord centered (shift of 3% from the center of the canal) in the canal for the both postures.
Characteristics lengths	Significantly different in neck flexion than in neutral supine position (+2 mm, 13mm and 18mm for the anterior column (LAC), posterior column (LPC) and spinal cord, respectively).

Table 3

1 Legends

2 **Table 1** : inter-and intra- mean relative errors for spinal cord (SC) and Cervical Subarachnoid Space (CSS) CSA and Antero-
3 posterior (AP) and Left – Right (LR) eccentricity indices. The averaged value, standard deviation, minimum and maximum
4 averaged value on the 5 subjects randomly selected are described as : [Mean \pm STD ; Min/Max]. The grey zones represent the
5 first tenth of the measures along the cervical cord and the white zones represent the rest.

6
7 **Table 2** : Distance errors (L2-norm in mm) per vertebra landmarks between operator 1 and the operator 2 (inter-operator
8 variability), as well as between 2-measurements sessions by operator 1(intra-operator variability). For each cell, the results
9 are presented as follow : [Mean ; Min/Max].

10

11 **Table 3** : summary table of the main results for each index.

12 **Supplemental Digital Content Table 4** : statistical summary [Mean \pm std (min/max)] of each measured parameter (SC and CSS
13 CSA, OR, AP/LR eccentricity and CR) for both position (neutral in white, flexion in gray). For each one, three sub-values are
14 given, corresponding to a spatial vertebral average of measures (AVD VERT, with C1 and C2 vertebrae merged : the C2 dens
15 passing through the ring of C1 vertebra), value picked up at the middle of the vertebra in the middle sagittal plan (MID VERT)
16 and value picked up at the middle of the intervertebral disc in the middle sagittal plan (MID IVD) , considering the disc below
17 the mentioned vertebral level). The LAC, LPC and LSC parameters correspond to the lengths of the anterior canal, posterior
18 canal and the spinal cord, along the whole cervical segment, respectively. *indicates $p < 0.05$ (Paired samples Wilcoxon test).

19

20 **Supplemental Digital Content Table 5** : table of CSA relative error [%] between manual and automatic CSA measurements for
21 5 subjects randomly selected. Mean and standard deviation were computed by averaging all subjects for seven levels along
22 the cervical spine.

23

24 **Figure 1 – a)** Sagittal view with superimposed 3D reconstruction of the SC (gold color) and the CSS (blue color) in flexion (left),
25 and neutral (right) neck positions. The red dotted lines indicates the delimitation of the cervical segment (C1-C7) considered
26 in this study. **b)** Main postprocessing steps, 3D reconstruction and 3D landmarks (left), orthogonal planes to the centerline all
27 along the cervical segment (middle), boundaries points (zoom x5) extracted from the intersection between 3D reconstruction
28 and the plane, with distance representations of eccentricity indices (A, P, L, R, \emptyset AP, \emptyset T) (right). **c)** As in Jha et al.²⁰, main steps
29 to compute the length of the cervical spinal cord (LSC) attached to the caudal side of the pons in red, length of the cervical
30 spinal anterior column (LAC) in yellow and length of the cervical spinal posterior column (LPC) in green (top : manual inputs,
31 bottom : 3D-spline interpolation).

32

33 **Figure 2** – (Top) Mean Cross-Sectional Area (CSA, mm^2) along the normalized cervical spinal normalized (see section 3.2 –
34 formula 6 for normalization process) segment of interest length, (bottom) Mean Occupation Ratio (% defined as SC CSA over
35 total canal CSA (SC CSA + CSS CSA)). For each subplot figure, the mean value of the neutral (blue continuous curve) and flexion
36 (red continuous curve) cases are indicated with their standard deviations (dot curve). Mean normalized positions of the
37 vertebral endplates (computed as the mean position of each vertebral endplates between all the subjects) are indicated with
38 color boxes and as vertical lines (small dots in flexion and bigger dots in neutral).

39

40 **Figure 3** – AP (top) and LR (middle) eccentricity indices along the normalized cervical cord, together with the Compression
41 Ratio index (bottom). For each subplot figure, the mean value of the neutral (blue continuous curve) and flexion (red
42 continuous curve) cases are indicated with their standard deviations (dotted curves). Mean normalized positions of the
43 vertebral endplates are indicated as well, standard deviations are not indicated on the figure for a sake of clarity.

44

45 **Figure 4** – Boxplots of characteristics lengths in the cervical segment, a) Length of the Anterior Column (LAC), b) Length of the
46 Posterior Column (LPC) c) Length of the Spinal Cord (LSC). On each box, the central mark indicates the median (red line), and
47 the bottom and top edges of the box indicate the 25th and 75th percentiles (horizontal blue lines), respectively. The whiskers
48 extend to the most extreme data points not considered outliers, and the outliers are plotted individually using the red '+'
49 symbol (* $p < 0.05$).

50

51 **Supplemental Digital Content Figure 5** – Spinal cord cross-sectional area (SC CSA) mean along the cervical. The mean value
52 of the neutral (blue continuous curve) and flexion (red continuous curve) cases are indicated with their standard deviations
53 (dotted curves). Mean normalized positions of the vertebral endplates are indicated as well standard deviations are not
54 indicated on the figure for a sake of clarity.







