Morphometric analysis of the cervical intervertebral foramina: Establishment of a normative database in Jordanians using 3-D reconstructed computed tomography images

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Abstract

Purpose

Despite overwhelming clinical importance, no accurate threshold values of linear measurements of cervical intervertebral foramina exist that signify the switch of cases from asymptomatic to symptomatic state. The pattern of change of relevant morphometric values with regard to different parameters remain inconclusive. In Jordan, morphometric analysis of normal cervical intervertebral foramina is still absolutely lacking. We intend to establish a normative database of the linear measurements of the cervical intervertebral foramina in a representative sample of normal Jordanian population. Age-, gender-, vertebral level-, and laterality-dependent differences of these measurements are to be explored.

Methods

Parasagittal computerized tomographic images of 320 normal Jordanians, 16–37 years of age, were stratified according to age and gender, three-dimensionally reconstructed, and foraminal height and width at the levels C2/C3 through C7/T1 were bilaterally measured and statistically analyzed.

Results

The overall average foraminal height and foraminal width measured: 10.15, 8.09, 8.00, 8.18, 8.43, and 7.97, and 6.34, 5.73, 6.03, 6.11, 6.83, and 7.33 (in mm), for the levels C2/C3 through C7/T1, respectively with mean ratio Width/Height was 0.77. A consistent reciprocal cranio-caudal pattern of decrease of height and increase of width was evident. Males showed consistently higher height and width values with level of significance reached at upper and lower intervertebral levels. Although statistically insignificant, the Adolescent age group showed the highest values of height and width among all other age groups. Significant side-related differences were lacking.

Conclusions

The linear parameters of normal cervical intervertebral foramina in Jordanians correspond well with other published studies, and follow differential, gender- and age-dependent, craniocaudal pattern of change relative to multiple variables.

Introduction

The intervertebral foramina, Latin: Foramina intervertebrales, or neural foramina can be regarded as anatomic portals providing for intra- and extravertebral space direct communication in a bilateral and segmental pattern throughout the length of the vertebral column [15]. From the descriptive perspective, the intervertebral foramina form the medial zone of the cervical nerve root sulcus, and are bounded by the adjacent vertebral pedicles inferiorly and superiorly, and the medial aspect of the facet joint and the adjacent part of the articular column posteriorly. Anteriorly lie the uncovertebral joint, the intervertebral disc, and the inferior part of the superjacent vertebra. Contents include the anterior and posterior spinal nerve roots, spinal ganglion, spinal vessels with ligamenta flava and loose connective fatty tissue completing the anatomic picture [10; 12]. From a 3-dimensional perspective, the intervertebral foramina lie in a rotated position with an angle of 45 ° in the coronal plane relative to the vertebral canal anteriorly, and 10–15° caudal inclination with the horizontal axis [9; 27].

The results of published studies dealing with morphometric analysis of normal cervical intervertebral foramina were frequently contradictory. In a differential description, the mean height of the neural foramina (FH) was insignificantly different at the levels C3/C4 to C7/T1, while the width (FW) behaved differently [1; 2; 12, 20, 26]. In a comprehensive study using magnetic resonance imaging, C2/C3 was shown to be the largest, C7/T1 the smallest, and C3/C4 through C6/C7 almost identical, mostly due to differences of the FH rather than the FW [24].

No consensus exists in the literature with respect to gender-related differences of the dimensions of cervical intervertebral foramina. Lack of significant gender-related differences of cervical intervertebral foraminal dimensions has been documented with the overall measurements reported to be less by 2% in females [12; 18].

A correlation between age and the morphometric evaluation of normal cervical intervertebral foramina could not be shown [29]. This contradicts, however, earlier reports which showed an age-related decrease of intervertebral foraminal width [21].

Previous findings regarding side-related differences of spinal morphologic values have been documented [25]. However, in normal, asymptomatic adults, the differences of the mean cervical intervertebral foraminal dimensions between right and left sides were reported to be statistically insignificant for either sex [1; 12; 24; 29]. In specific terms, although the left cervical foramina were shown to exhibit higher values of foraminal measurements, especially the FH, however, this difference was statistically insignificant [5].

To the best of our knowledge, the existing literature lacks studies on cervical intervertebral foraminal morphometric evaluation in normal Jordanian population. Moreover, reliable and accurate threshold values for any morphometric parameter of cervical intervertebral foramina, which would advocate the transition from normal to abnormal state in the absence of clinical manifestations are not yet defined.

The anticipated objectives of this study can be formulated as:

1. To build up a normative database of the linear measurements of the normal cervical intervertebral foramina C2/C3 through C7/T1 in Jordanian population.

2. To explore age-, gender-, vertebral level-, and side-dependent differences of the measurements of cervical intervertebral foramina, and describe patterns of change of these parameters.
3. To compare the measurements of the cervical intervertebral foramina in Jordanian population with corresponding measurements published in the literature.
4. To provide for explanations and discuss possible reasons for contradictory findings in the literature.

Materials And Methods

Sample of Study (Table I)

A total number of 320 cases (214 males and 106 females, 16–37 years of age) were collected retrospectively from the archives of the patients' records in the Department of Radiology and Nuclear Medicine at King Abdullah University Hospital (KAUH): a referral university teaching hospital, affiliated to Jordan University of Science and Technology (JUST). All cases were examined in the department during the period from 2017–2019 with the chief complaint of neck pain. Each gender group was divided into three age subgroups: Adolescence age group (16–19 years of age), youth age group (20–24 years of age), and adult age group (25-37years of age), in accordance with World Health Organization (WHO) definitions. All cases were judged as normal with regard to the cervical vertebral region by two consultant radiologists in the Department of Radiology and Nuclear Medicine at KAUH. Parasagittal computed tomographic images for these cases were taken on right and left sides, thickness 2.0 mm, using Brilliance 64-slice CT scanner (by PHILIPS) in the neutral position of the head and neck.

Methods

Tomographic images were three-dimensionally reconstructed using synapse computer program (Synapse PACS system, by Fujifilm) including all cervical intervertebral foramina C2/C3 through C7/T1 bilaterally. C1/C2 foramen was excluded. Measurements were performed on a computer screen and were displayed to the nearest 0.01 mm. Landmarks were placed at the most superior point of the inferior pedicle (H), the most inferior point of the superior pedicle (H’). Foraminal height (FH) was identified as the maximum distance joining the superior and inferior foraminal margins in the sagittal plane as a line joining H-H’. Foraminal width (FW) was set as a line (W-W’) passing through the midpoint of the line of the foraminal height at right angles reaching the foraminal margins on both sides (Figs. 1–7). To avoid bias during the measurements, all the images were coded numerically, and all further work was performed referring to these codes. Only after all the measurements were completely recorded and archived, the corresponding personal data for each case and code were paired and taken into consideration for data statistical analysis.

Statistics

All measurements were tabulated according to gender and age group (Tables I-IV). For each age group and in both genders, and for each intervertebral level and side, the basic statistics were performed for each of the linear measurements. Statistical analysis was performed by transferring the data into a scientific statistical program (GraphPad Prism scientific 2-D graphing and statistics software, California, USA). Statistical differences between means of sets of measurements were compared using Student's t-test for independent data with significance level of 5% (P 0.05).

Error Analysis

Errors of measurements were determined by remeasuring the FH and FW of randomly chosen 48 cases (24 cases for each gender, and 8 cases per age group) by the same investigator at two separate occasions (4 weeks apart). Original and repeated sets of measurements were analyzed for significance of differences. All statistical tests were two-sided and were performed at a significance level of P 0.05 using PRISM statistical software.

Results

Case Distribution

Table I shows the general and specific group and subgroup case number and distribution. Expressed in percentages, males accounted for 66.9% of total sample. The adolescence, youth, and adult age categories represented 15.4%, 38.3%, and 46.3%, respectively. Females, accounted for 33.1% of the total sample, of which the adolescence, youth and adult age categories were 17%, 44.3%, and 38.7%, respectively. The overall adolescence groups accounted for 15.9%, while the overall youth and adult age groups were represented by 40.3% and 43.8% of the total sample.

Measurements

Tables II-IV show the total values and standard deviations of FH and FW, in males and females, on the right and left sides, and the total values and standard deviations of foraminal height and width, in the adolescence, youth, and adult age groups, in males and females, on the right and left sides. Our results reveal that the overall average FH and FW score: 10.15, 8.09, 8.00, 8.18, 8.43, and 7.97, and 6.34, 5.73, 6.03, 6.11, 6.83, and 7.33 (in mm), for the levels C2/C3 through C7/T1, respectively. The mean of the ratio FW/FH mounts to 0.77. An obvious and consistent cranio-caudal pattern of increase of this ratio is observed, where relative minimal and maximal ratios are evident at the levels of C2/C3 and C7/T1, respectively. This pattern remains valid, irrespective of age, gender, or side.

Table V shows the overall mean values of original and repeated measurements (48 cases) of FH and FW at all measured intervertebral levels, irrespective of age, gender, and side, and the P-values of t-test at different intervertebral levels. No significant differences between original and repeated measurements could be calculated.

Figure 8A shows the values and standard deviations of FH in males and females at all the measured intervertebral levels on the right side. FH is maximal at the level of C2/C3 and drops down to reach a minimal value at the level of C7/T1. The males show consistently higher values of this parameter at all intervertebral levels, which reaches the level of significance at upper intervertebral levels (C2/C3) and at lower intervertebral levels (C7/T1). The most obvious drop of values along the sequence of intervertebral levels is evident between C2 and C3, and between C3 and C4. A comparable obvious drop can be documented between C6 and C7, and between C7 and T1.

Figure 8B shows the values and standard deviations of FH in all cases, males and females, at all the measured intervertebral levels on the left side. Maximal FH values are measured at the intervertebral level of C2/C3 and lowest values at the level of C7/T1. The values of this parameter fluctuate inconsistently between the intervertebral levels of C3/C4 and C6/C7. Gender-related differences in favor of males acquire significant levels at the intervertebral levels of C2/C3, C3/C4, and C7/T1.

Figure 8C shows the values and standard deviations of FW in males and females at all the measured intervertebral levels on the right side. FW shows a maximum value in both genders at the lowest intervertebral levels (C7/T1). The minimal levels of this parameter are evident at the level of C3/C4. Starting from the level of C3/C4 a gradual increase of width is observed towards C7/T1. Males show significantly higher width values only at the level of C7/T1.

Figure 8D shows the values and standard deviations of FW in all cases (males and females) at all the measured intervertebral levels on the left side. The highest values are measured at the intervertebral level of C7/T1. A pattern of decrease of this parameter is observed along the intervertebral levels reaching C3/C4. The intervertebral level of C2/C3 shows an increase of this parameter and approaches values seen at the level of C6/C7. Gender-related differences in favor of males are seen at the intervertebral levels of C7/T1 and C2/C3. Significance is reached, however, at the level of C7/T1. Male-female differences are inconsistent elsewhere along the intervertebral levels.

Figure 9A shows the values and standard deviations of FH in adolescence, youth, and adult age groups in males at all the measured intervertebral levels on the right side. FH shows maximal values at the highest intervertebral levels C2/C3 in all three age groups. An obvious drop of this parameter is seen already at the level of C3/C4. Adolescent age group shows the highest values of this parameter at all intervertebral levels in comparison with youth and adult age groups.

Figure 9B shows the values and standard deviations of FH in adolescence, youth, and adult age groups in males at all the measured intervertebral levels on the left side. The maximal levels are measured at the intervertebral level of C2/C3, irrespective of age-groups or gender. An obvious decrease of this parameter is noticed between C2/C3 and C3/C4 and between C3/C4 and C4/C5. Minimal values of this parameter are evident at the intervertebral level of C7/T1, but values remain inconsistent between the intervertebral levels of C4/C5 and C6/C7. Adolescent age group always shows higher values of this parameter than the other two age groups. The differences between youth and adult age groups are only slight at the intervertebral levels between C3/C4 and C7/T1.

Figure 9C shows the values and standard deviations of FW in adolescence, youth, and adult age groups in males at all the measured intervertebral levels on the right side. The maximal values are evident at the lowest intervertebral levels C7/T1 in all age groups. An obvious pattern of decrease of this parameter is consistent through the intervertebral levels up to C2/C3. Maximal values are seen in the adolescent age group at all intervertebral levels. A similar obvious difference is seen when youth and adult age groups at all intervertebral levels are compared.

Figure 9D shows the values and standard deviations of FW in adolescence, youth, and adult age groups in males at all the measured intervertebral levels on the left side. The highest values are measured at the intervertebral level of C7/T1, irrespective of age group. A gradual decrease of this parameter is evident along the intervertebral levels reaching C3/C4. The intervertebral level of C2/C3 approaches FW values which are measured at the level of C4/C5. Adolescence age group shows consistently higher values of this parameter than other age groups. Age-related differences between adolescence and youth groups on one hand, and between youth and adult age groups, on the other hand are obviously seen across all intervertebral levels. Minimal values of this parameter are reached at the intervertebral level of C3/C4, irrespective of age group.

Figure 10A shows the values and standard deviations of all FH in adolescent, youth, and adult age groups of all cases in females at all the measured intervertebral levels on the right side. Maximal values are evident at the intervertebral level of C2/C3, and are lowest at the level of C7/T1. An obvious decrease of this parameter is noticeable between the intervertebral levels of C2/C3 and C3/C4 and between C6/C7 and C7/T1.

Figure 10B shows the values and standard deviations of FH in adolescence, youth, and adult age groups in females at all the measured intervertebral levels on the left side. Maximal values are measured at the intervertebral level of C2/C3 and are lowest at the levels of C4/C5 and C7/T1. This parameter shows almost equal values along the intervertebral levels C3/C4 and C6/C7. Adolescence age group shows maximal values of this parameter, which are almost equal to the corresponding values of the youth age group, irrespective of intervertebral level, except for C2/C3. FH values in the adult age group are remarkably and consistently lower than the previous two age groups.

Figure 10C shows the values and standard deviations of all FW in adolescent, youth, and adult age groups of all cases in females at all the measured intervertebral levels on the right side. Maximal values are evident on the intervertebral level of C7/T1. A gradual drop of this parameter is noticed moving along the intervertebral levels reaching the level of C3/C4. The level of C2/C3 exhibits high values which approach those belonging to the levels of C4/C5 and C5/C6.

Figure 10D shows the values and standard deviations of FW in adolescence, youth, and adult age groups in females at all the measured intervertebral levels on the left side. Maximal values are measured at the intervertebral level of C7/T1. A gradual decrease of this parameter is evident along the intervertebral levels approaching C3/C4 with an only slight increase of this parameter at the level of C2/C3. The youth age group shows the highest levels of this parameter at all intervertebral levels and approach equality with adolescence age group at all intervertebral levels, except for C2/C3, C3/C4, and C7/T1. The adult age group shows consistently the lower values of this parameter, irrespective of intervertebral level, except for C2/C3.

Discussion

General statement

The current work represents the first morphometric study of normal cervical intervertebral foramina in Jordanian population. The age spectrum therein was set to ensure that the body skeletal growth phase has already been established, and the process of physiological adaptation to lifestyle, including nutrition, occupation, physical activity, and skeletal remodeling has already set in. The absence of ensuing spine degenerative changes was affirmed through radiologic evaluation. We can, therefore, assume that all our measurements most likely represent normal morphometric descriptive values for the Jordanian population in pre-adult and adult age.

Relevance and importance of the study

The relevance of conducting this descriptive research is academic and clinical in nature. The 3-dimensional anatomy of cervical intervertebral foramina is by no means luxurious database to achieve successful performance of surgical procedures and minimizing iatrogenic injuries [30].

The necessity of adequate evaluation of the dimensions of the intervertebral foramina and establishing a normative database of the morphometric analysis of this structure cannot be to overemphasized in order to be able to confirm or exclude foraminal stenosis [16].

The methodology

In addition to high spatial resolution and better direct visualization, 3-D reconstructed computer tomography offers adequate means of rotating the images in the desired directions, thus compensating for the normally tilted position of cervical intervertebral foramina and obtaining face on views thereof [27], which adds substantially to the accuracy and reliability of measurements.

Inter-studies and inter-racial differences

For the purpose of comparison of our measurements with corresponding published data, representative studies in the literature [1; 5, 24] were chosen on basis of comparable study samples and methodologies (Table VI). This comparison clearly shows considerable similarity regarding FH and FW values of cervical intervertebral foramina. However, it should be kept in mind, that inter-population variations make inter-study comparisons of only limited value as previously suggested [29]. In the light of our results, it could be assumed, nevertheless, that inter-population differences are negligible, once the choice of study cases and of the measurement techniques and parameters definitions are relatively unified.

Level-dependent measurements

Our data showed that the overall mean values of FH, irrespective of age, gender, or side exhibited an average craniocaudal decrease of 23% between maximal and minimal values at the levels of C2/C3 and C7/T1, with the most obvious drop of values along the sequence of intervertebral levels evident between C2/C3 and C3/4 (20%). Between the levels C3/C4 through C6/C7 the change is inconsistent and the percentage of either increase or decrease between successive levels. On the other hand, the overall mean values of FW exhibited an average craniocaudal difference of 20% between the maximal values at the lowest intervertebral levels (C7/T1) and the minimal level of this parameter at the level of C3/C4. The gradual increase of FW towards C7/T1 became increasingly obvious averaging 12% at the lowest intervertebral levels. In spite of the overall cranio-caudal increase pattern, however, it is interesting to note that an initial decrease of width is seen between C2/C3 and C3/C4 averaging 9%. This reciprocal cranio-caudal pattern of FH and FW of normal cervical intervertebral foramina confirms the findings of Barakat and Hussein [2]. The differential behavior resides probably in the nature of two components. On one hand, the skeletal set up of the foramina in response to mechanical burden put on successive vertebrae along the cervical spine may play a determining role. On the other hand, the relative varying size of the neural and vascular structures the intervertebral foramina house at different vertebral levels may contribute significantly to this pattern. In this regard, the size of the intervertebral foramen has been reported to vary depending on axial loading [14]. In fact, radiculopathy has been reported to mostly affect C7 followed by C6 [4]. The pattern of increasing FW in caudal cervical intervertebral foramina and increased mean cross-sectional area thereof has been already documented, and may, therefore, create more space for the different structures normally residing or passing through the foramina at these levels [1; 11; 20; 26]. In fact, the brachial plexus roots [3], and prominent vascular elements [10], may necessitate increased FW in lower cervical intervertebral foramina. In contrast, upper cervical nerve roots were reported to be smaller than their lower counterparts [27]. The greater dimensions of the cervical intervertebral foramen at the level C2/C3, as clearly evident in our results, could be related to the large size of anterior epidural venous plexus, an anterolateral structure, being prominent at this level, as it has been already demonstrated [13], and could explain the results of Lentell et al. [24], who found that FH, rather than FW, was responsible for C2/C3 being the largest. This differential cranio-caudal pattern of linear parameters could account for some of the contradictory findings reported in the literature regarding level-dependent, varying results of cervical intervertebral foraminal area and volume. The differential impact of each linear parameter could find its relative echo on foraminal area or volume at any particular vertebral level in accordance with the differential degree this linear value plays in determining the value of foraminal area of volume.

The impact of age

The adolescence, youth, and adult age groups in our study are expected to lie within an expected non-degenerative phase of development, as verified by clinical and radiological inclusion criteria adopted. The analysis of our results revealed that, irrespective of gender or side, the adolescent age group consistently showed the highest FH values at all intervertebral levels when compared with the other two age groups. This difference averaged 8% and 11% when adolescence age group is compared with youth and adult age groups at all levels. Similarly, the youth age group consistently showed greater FH values averaging 4% as compared with adult age group at all intervertebral levels. The FW values displayed identical age-related pattern of change to FH values, irrespective of gender or side. The highest FW values were seen in the adolescent age group as compared with the youth and adult age groups (7% and 14%) at all intervertebral levels, with an obvious cranio-caudal pattern of increase. Similarly, the youth age group exhibited higher FW values than the adult age group at all intervertebral levels (7%) at all the levels with a similar cranio-caudal pattern of increase of difference. In the light of our data, it becomes reasonable to speculate, that osseous growth with respect to linear dimensions of the cervical intervertebral foramina reaches its summit already at the end of the adolescence phase. Thereafter, and in the absence of degenerative changes, the foramina go through a process of remodeling, as evident by insignificant narrowing of linear diameters. Lower cervical segments seem to be especially involved. Moreover, it should be taken into consideration, that significant non-pathologic, age-dependent changes of cervical intervertebral foraminal dimensions, which are associated with ongoing bone remodeling can be expected, which probably run subtly towards eventual pathologic change at some point of advancing age Interestingly, aging has been reported to be associated with decreased number of myelinated fibers in spinal nerve roots [6; 11], although a correlation between age and nerve size was shown to be lacking [19].

Lentell et al. [24], Rühli et al. [29], and Cramer et al. [8] worked on age-stratified cases including the age spectrum present in our study. The authors reached the conclusion that their obtained data from normal vertebrae showed almost always lack of correlation between individual age and intervertebral foraminal size. In contrast, Humphreys et al. [21] reported that cervical intervertebral FW, but not FH, decreased with age. The differential mode of change i.e., the decrease of FH without concurrent increase of superior FW with age has been reported, and has been proposed to reflect subtle disc narrowing or mild collapse of the vertebral bodies with age [7].

Gender-related differences

The analysis of our data revealed interesting, inter-gender differences in terms of age, side, and intervertebral level. The overall mean values of the FH in males were consistently higher at all intervertebral levels. These differences reached the level of significance at upper intervertebral levels (C2/C3) and at lower intervertebral levels (C7/T1) with mean percentage of difference of 8.5%, irrespective of the side. On the other hand, the overall mean values of the FW revealed only unremarkable and inconsistent inter-gender differences, with significance reached, only at the level of C7/T1 in favor of males. However, and elsewhere across the vertebral levels, male versus female FW differences were in favor of females, although these differences remained statistically insignificant. Accordingly, it becomes plausible to suggest, that a differential FH versus FW sex dimorphism apparently exists. This differential pattern appears to be vertebral level-dependent. Superior and inferior ends of cervical spine seem to show higher values in favor of males, where differences reach statistical significance. Middle cervical levels show the opposite pattern. This differential pattern may account for frequent inconsistencies reported in the existing literature in this regard. In general terms, Jankauskas [22] put forward the notion of stronger impact of the gender, rather than the age, on vertebral dimensions in favor of males. However, such a difference has been shown to be lacking [18]. In specific terms, females were shown to have slightly, statistically insignificantly smaller normal cervical intervertebral FH, FW, and area [1; 20; 24; 29]. In contrast, reversed sexual dimorphism of the FW values of cervical intervertebral foramina in favor of females was claimed [12]. Indeed, the size of spinal structures that enclose neural structures has been long found to favor females [17]. Porter et al. [28] speculated that the amount of epidural fat may be greater in females with subsequent larger neural foramina.

Right versus left side differences

Allometry issues resonated their echo in the field of morphometry of cervical intervertebral foramina. The analysis of our data showed that differential side-related differences of FH, but not FW values, were evident. However, these differences, in favor of the right side at caudal cervical intervertebral levels, and in favor of left side at cranial segments, remained statistically insignificant. Data retrieved from the literature showed that no significant differences between the right and left sides exist regarding cervical intervertebral FH, FW, or area [1, 24]. In specific, left cervical foramina were shown to exhibit higher values of foraminal measurements, especially of FH, which, however, did not cross the statistical significance threshold [5]. On the other hand, it has been advocated that significant right versus left differences of the dimensions of normal cervical intervertebral foramina, irrespective of gender, could to be related to the size of passing structures i.e. brachial plexus roots, which could be correlated with handedness, occupation, constitution, and social differences [3]. It is obvious that simple allometry rules are not a major factor regarding the dimensions of cervical intervertebral foramina. It is interesting to note, in this regard, that statistically significant differences exist between the nerve roots of cervical intervertebral foramina on the right and left sides [23]. Nevertheless, the use of the dimensions of an intervertebral foramen on a particular side, at one particular level, as normal reference to judge the patency of its counterpart at the same level on the opposite side remains justified [8].

Conclusions

Based on our results and in the light of our discussion, and taking into consideration relevant data we could retrieve from the literature, we could reach the following conclusions:

1. The data we presented in this study can be regarded as a normative database of the dimensions of cervical intervertebral foramina in Jordanian population.

2. 3-D reconstructed computerized tomographic images offer an accurate, reproducible, and authentic approach to conduct morphometric analysis of the cervical intervertebral foramina, and could be advocated as standard first line investigation in cases with neck pain.
3. Our results relate well, and can be viewed as complementary data for other similar studies already published in the literature.
4. Vertebral level-related differences point to differential cranio- caudal pattern of consistent change in from of increase of width and decrease of height.
5. Age-related differences within the present age spectrum reflect physiological adaptation to axial load and life style.
6. Gender-related differences most probably reflect general inter-gender constitutional differences.
7. Side-related differences may reflect level-dependent adaptation to handedness.
8. The multifactorial-dependent differential pattern of differences probably accounts for inconsistencies reported in the literature.
9. Further research is needed to elucidate changes of foraminal dimensions beyond the expected limits of “normal”.

Declarations

Author Contribution

EA Momani designed the project, made preliminary selection of cases, performed all measurements and data management, and made major contribution to writing of the manuscript. JA Ghaida, as the principal supervisor, co-designed the research, supervised all steps of the project, and followed up the analysis of data, and made major contributions to the editing of the manuscript. O Aldaoud and W Marashdeh made valuable clinical contribution to the selection of cases, and the measurement methodology. AA Al-Mousa made major contributions to the analysis of data. Z Bataineh co-supervised the progress of the project, and proofread the manuscript. All authors have read and approved of the final version of this manuscript.

Conflict of Interest

The authors declare that they have no conflict of interest.

The authors declare that the research was conducted in the absence of ant commercial or financial relationships that could construed as a potential conflict of interest

Ethical Approval

All applicable international, national, and institutional guidelines for the care and use of data obtained after conceit of patients and were approved by the ethical committee of the Faculty of Research at Jordan University of Science and Technology in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki and all subsequent revisions. Patient anonymity was preserved.

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Tables

Table I: The general and specific group and sub-group case distribution.

Total sample No = 320					
Female group Number = 106			Male group Number = 214		
Female adolescent age category No = 18	Female youth age category No = 47	Female adult age category No = 41	Male adolescent age category No = 33	Male youth age category No = 82	Male adult age category No = 99
Overall adolescent age category (16-19 years old) No = 51		Overall youth age category (20-24 years old) No = 129		Overall adult age category (25-37 years) No = 140	

Table II: The mean values and standard deviations of the FH and FW in males and females at all the measured intervertebral levels on the right and left sides: (RH), (LH), (RW), and (LW) (all in mm).

Measurement	RH C2/C3	RHC3/C4	RH C4/C5	RH C5/C6	RH C6/C7	RH C7/T1
Male group (N = 114)	10.58±1.41	8.36±1.36	8.14±1.22	8.23±1.22	8.69±1.35	8.22±1.17
Female group (N = 106)	9.65±1.18	7.89±1.23	7.90±1.17	7.96±1.17	8.18±1.13	7.56±1.31
Measurement	RW C2/C3	RW C3/C4	RW C4/C5	RW C5/C6	RW C6/C7	RW C7/T1
Male group (N = 114)	6.48±1.31	5.77±1.33	6.02±1.34	6.18±1.32	7.06±1.35	7.64±1.44
Female group (N = 106)	6.31±1.10	5.90±1.14	6.28±1.13	6,29±1.02	7.07±1.23	7.23±1.26
Measurement	LH C2/C3	LH C3/C4	LH C4/C5	LH C5/C6	LH C6/C7	LH C7/T1
Male group (N = 114)	10.66±1.48	8.25±1.36	8.16±1.20	8.40±1.20	8.58±1.34	8.17±1.15
Female group (N = 106)	9.70±1.39	7.84±1.15	7.77±1.18	8.10±1.26	8.26±1.16	7.49±1.06
Measurement	LW C2/C3	LW C3/C4	LW C4/C5	LW C5/C6	LW C6/C7	LW C7/T1
Male group (N = 114)	6.53±1.32	5.83±1.31	6.12±1.31	6.25±1.30	6.84±1.31	7.75±1.46
Female group (N = 106)	6.33±1.17	5.93±1.12	6.23±1.15	6.42±1.09	6.87±1.14	7.16±1.27

Table III: The mean values and standard deviations of the FH and FW in adolescence, youth, and adult age groups in males at all the measured intervertebral levels on the right and left sides: (RH), (LH), (RW), and (LW) (all in mm).

	RH C2/C3	RH C3/C4	RH C4/C5	RH C5/C6	RH C6/C7	RH C7/T1
Male Adolescence (N = 33)	11.21±1.56	9.05±1.63	8.52±1.44	8.88±1.21	9.43±1.22	8.90±1.09
Male Youth (N = 82)	10.59±1.18	8.36±1.30	8.27±1.16	8.28±1.13	8.60±1.25	8.16±1.25
Male Adults (N=99)	10.37±1.48	8.13±1.25	7.91±1.15	7.98±1.22	8.52±1.40	8.04±1.06
	RW C2/C3	RW C3/C4	RW C4/C5	RW C5/C6	RW C6/C7	RW C7/T1
Male Adolescence (N = 33)	6.74±1.56	6.50±1.47	6.86±1.55	7.11±1.49	7.89±1.69	8.35±1.40
Male Youth (N = 82)	6.56±1.21	5.76±1.21	6.12±1.29	6.34±1.21	7.12±1.19	7.74±1.46
Male Adults (N=99)	6.33±1.30	5.53±1.30	5.65±1.17	5.74±1.15	6.73±1.23	7.32±1.36
	LH C2/C3	LH C3/C4	LH C4/C5	LH C5/C6	LH C6/C7	LH C7/T1
Male Adolescence (N = 33)	11.68±1.69	9.30±1.45	8.75±1.46	9.12±1.33	9.62±1.01	8.85±1.08
Male Youth (N = 82)	10.73±1.34	8.20±1.17	8.25±1.06	8.40±0.98	8.50±1.23	8.18±1.22
Male Adults (N=99)	10.27±1.36	7.95±1.31	7.88±1.14	8.16±1.22	8.30±1.37	7.92±1.02
	LW C2/C3	LW C3/C4	LW C4/C5	LW C5/C6	LW C6/C7	LW C7/T1
Male Adolescence (N = 33)	6.90±1.72	6.65±1.51	6.83±1.67	7.15±1.37	7.67±1.31	8.65±1.33
Male Youth (N = 82)	6.61±1.24	5.83±1.25	6.27±1.14	6.44±1.30	7.00±1.33	7.75±1.38
Male Adults (N=99)	6.34±1.21	5.55±1.19	5.76±1.20	5.78±1.08	6.41±1.13	7.45±1.44

Table IV: The mean values and standard deviations of the FH and FW in adolescence, youth, and adult age groups in females at all the measured intervertebral levels on the right and left sides: (RH), (LH), (RW), and (LW) (all in mm)

	RH C2/C3	RH C3/C4	RH C4/C5	RH C5/C6	RH C6/C7	RH C7/T1
Female Adolescence (N=18)	10.18±1.46	8.97±1.32	8.72±1.23	8.90±1.04	8.84±0.75	7.81±1.29
Female Youth (N=47)	9.91±1.17	8.01±1.17	8.00±1.17	8.05±1.21	8.30±1.28	7.77±1.40
Female Adult (N=41)	9.10±1.00	7.27±0.85	7.42±0.91	7.44±0.87	7.75±0.93	7.20±1.14
	RW C2/C3	RW C3/C4	RW C4/C5	RW C5/C6	RW C6/C7	RW C7/T1
Female Adolescence (N=18)	6.36±1.18	6.06±1.08	6.36±0.85	6.72±0.85	7.26±0.94	7.23±1.30
Female Youth (N=47)	6.44±1.05	6.09±1.17	6.42±1.19	6.38±1.03	7.19±1.10	7.40±1.21
Female Adults (N=41)	6.14±1.14	5.60±1.11	6.09±1.16	6.00±1.02	6.84±1.46	7.05±1.31
	LH C2/C3	LH C3/C4	LH C4/C5	LH C5/C6	LH C6/C7	LH C7/T1
Female Adolescence (N = 18)	10.18±1.46	8.97±1.32	8.72±1.23	8.90±1.04	8.84±0.75	7.81±1.29
Female Youth (N = 47)	9.91±1.03	8.01±1.17	8.00±1.17	8.05±1.21	8.30±1.28	7.77±1.40
Female Adults (N=41)	9.10±1.00	7.27±0.85	7.42±0.91	7.44±0.87	7.75±0.93	7.20±1.14
	LW C2/C3	LW C3/C4	LW C4/C5	LW C5/C6	LW C6/C7	LW C7/T1
Female Adolescence (N = 18)	6.23±1.00	5.92±1.10	6.28±1.07	6.54±0.99	6.96±0.71	7.13±1.36
Female Youth (N = 47)	6.45±1.25	6.16±1.02	6.36±1.19	6.57±1.02	6.99±1.22	7.36±1.18
Female Adults (N=41)	6.24±1.15	5.67±1.20	6.06±1.15	6.19±1.18	6.68±1.21	6.95±1.31

Table V: The overall mean values and standard deviations of original and repeated measurements of FW (RW, LW) and FH (RH, LH) (48 cases) (all in mm) and the P-values of correlation t-test at all intervertebral levels on the right and left sides, irrespective of age or gender.

	Mean	SD	*P* (after *t* test)
RWC2/3	10.10532	0.4025	0.7458
RWC3/4	8.269792	0.2994	0.6664
RWC4/5	8.178125	0.1710	0.2782
RWC5/6	8.182292	0.1902	0.5977
RWC6/7	8.544792	0.4584	0.3996
RWC7/T1	7.934375	0.6912	0.7872
LWC2/3	6.465625	0.5901	0.3701
LWC3/4	6.088542	0.7037	0.4278
LWC4/5	6.236458	0.4959	0.5440
LWC5/6	6.564583	0.4816	0.1745
LWC6/7	6.822917	0.3815	0.1571
LWC7/T1	7.344792	0.4120	0.8074
RHC2/3	6.259375	0.4302	0.0713
RHC3/4	5.811458	0.2666	0.2192
RHC4/5	6.180208	0.3482	0.7730
RHC5/6	6.335417	0.4212	0.9457
RHC6/7	7.001042	0.4050	0.2749
RHC7/T1	7.576042	0.8223	0.7935
LHC2/3	10.11458	0.5275	0.7034
LHC3/4	8.233333	0.3565	0.4697
LHC4/5	8.05	0.2440	0.5571
LHC5/6	8.2375	0.4932	0.6008
LHC6/7	8.34375	0.4785	0.0677
LHC7/T1	7.835417	0.2209	0.6967

Table VI: Comparison of mean values of cervical intervertebral FH and FW at the levels C2/C3 through C7/T1 (all in mm) in the current study and representative studies in the literature. * Lentell et al. [24]; ** Chang et al. [5]; *** Ahmed et al. [1].

Study	Country	Material	C2/C3		C3/C4		C4/C5		C5/C6		C6/C7		C7/T1	
			Rt	Lt	Rt	Lt	Rt	Lt	Rt	Lt	Rt	Lt	Rt	Lt
Current study FH	Jordan	3-D CT	10.12	10.18	8.13	8.05	8.02	7.97	8.10	8.25	8.44	8.42	7.89	8.04
Current study FW	Jordan	3-D CT	6.24	6.43	5.57	5.88	5.87	6.18	5.87	6.34	6.79	6.86	7.19	7.46
Current study FH	Jordan	3-D CT	10.15		8.09		8.00		8.18		8.43		7.97	
Current study FW	Jordan	3-D CT	6.34		5.73		6.03		6.11		6.83		7.33	
FH (*)	USA	MRI	12.2		9.9		10.5		10.5		10.5		10.0	
FW (*)	USA	MRI	8.3		7.2		6.8		6.9		7.1		6.9	
FH (**)	USA	3-D CT			8.60		8.30		8.17		8.61			
FW (**)	USA	3-D CT			7.61		6.38		6.95		7.15			
FH (***)	Egypt	Radiogram			9.0	9.0	11.0	10.0	11.0	10.0	13.0	12.0		
FW (***)	Egypt	Radiogram			8.0	8.0	9.0	8.0	10.0	8.0	9.0	9.0		

Figures

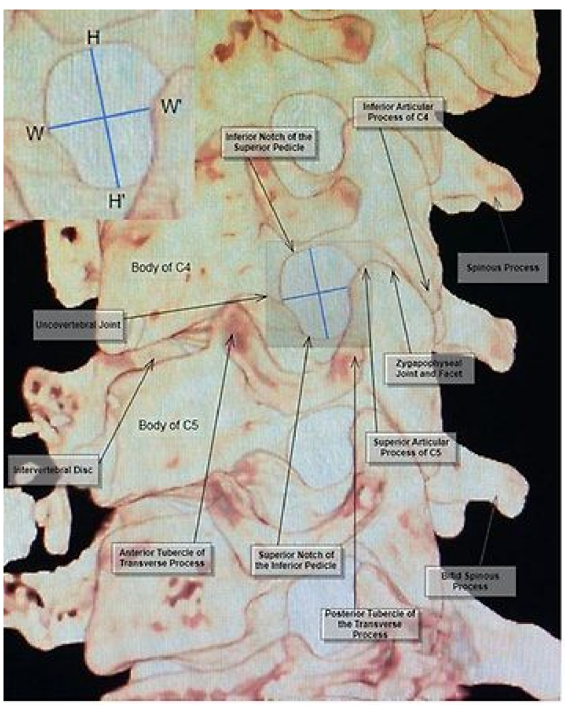

Figure 1

A 3D reconstructed computed tomographic image showing the main anatomical landmarks of the cervical vertebrae and intervertebral foramina, the zoomed section shows an illustration of the measurements of the intervertebral foramen; H: the most superior point of the inferior pedicle, H': the most inferior point of the superior pedicle, W: the anterolateral aspect of the superior vertebral body inferior notch, W': the posterolateral aspect of the inferior vertebral body superior notch, FH (H-H'): the maximum distance joining the superior and inferior foraminal margins in the sagittal plane, FW (W-W'): the line passing through the midpoint of the line of the FH at right angles reaching the foraminal margins on both sides.

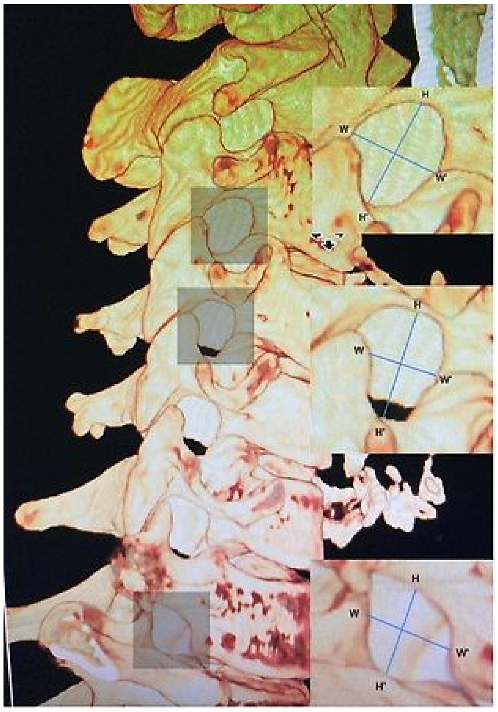

Figure 2

A 3D reconstructed computerized tomographic image of a female of the adolescent age group showing the right cervical intervertebral foramina from C2/C3 to C7/T1. The zoomed C2/C3, C4/C5, C7/T1 foramina show cranio-caudal pattern of decrease in FH and increase in FW.

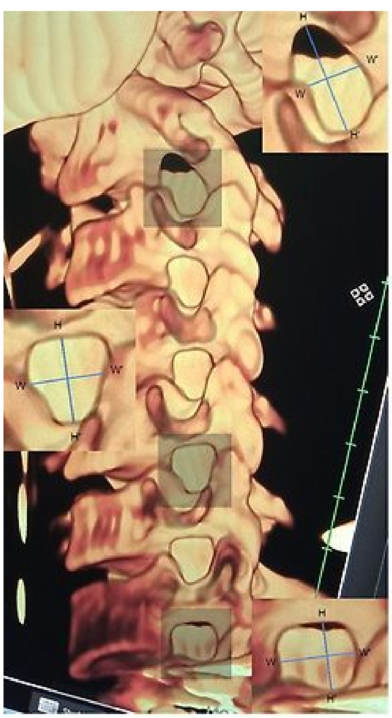

Figure 3

A 3D reconstructed computerized tomographic image of a male of the adolescent age group showing the right cervical intervertebral foramina from C2/C3 to C7/T1. The zoomed C2/C3, C4/C5, C7/T1 foramina show cranio-caudal pattern of decrease in FH and increase in FW.

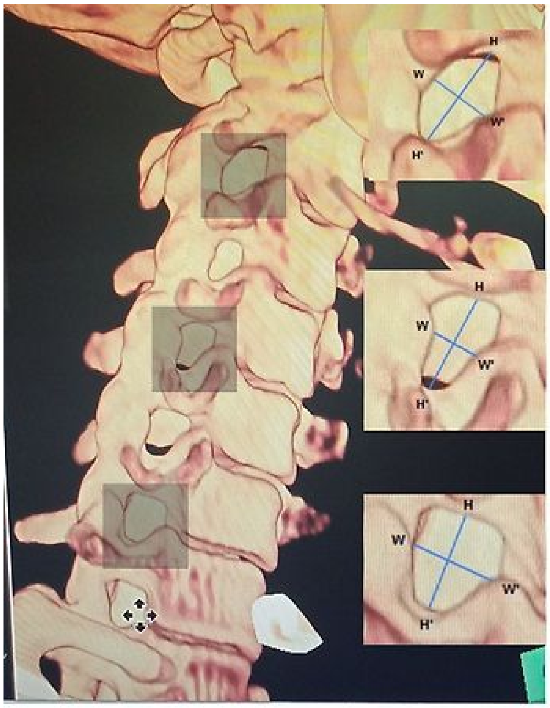

Figure 4

A 3D reconstructed computerized tomographic image of a female of the youth age group showing the left cervical intervertebral foramina from C2/C3 to C7/T1. The zoomed C2/C3, C5/C6, C7/T1 foramina show cranio-caudal pattern of decrease in FH and increase in FW.

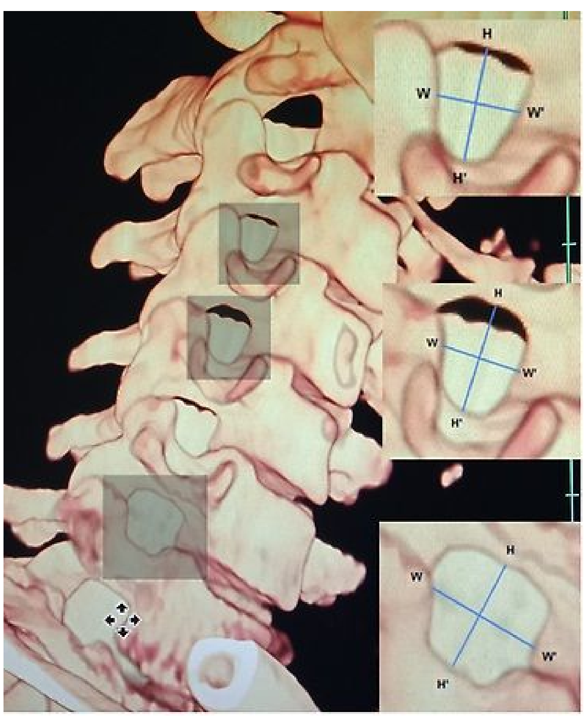

Figure 5

A 3D reconstructed computerized tomographic image of a male of the youth age group showing the left cervical intervertebral foramina from C2/C3 to C7/T1. The zoomed C2/C3, C4/C5, C7/T1 foramina show cranio-caudal decrease in FH and increase in FW.

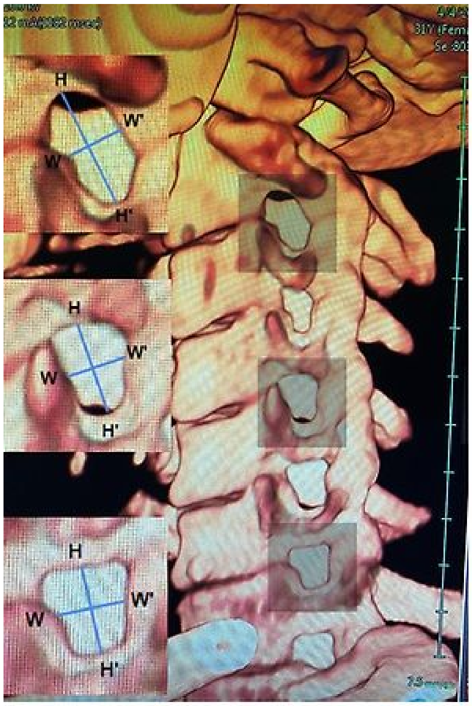

Figure 6

A 3D reconstructed computerized tomographic image of a female of the adult age group showing the right cervical intervertebral foramina from C2/C3 to C7/T1. The zoomed C2/C3, C5/C6, C7/T1 foramina show cranio-caudal pattern of decrease in FH and increase in FW.

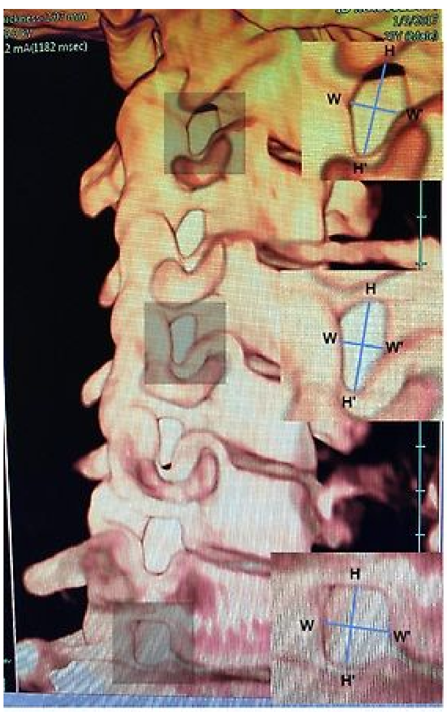

Figure 7

A 3D reconstructed computerized tomographic image of a male of the adult age group showing the right cervical intervertebral foramina from C2/C3 to C7/T1. The zoomed C2/C3, C4/C5, C7/T1 foramina show cranio-caudal pattern of decrease in FH and increase in FW.

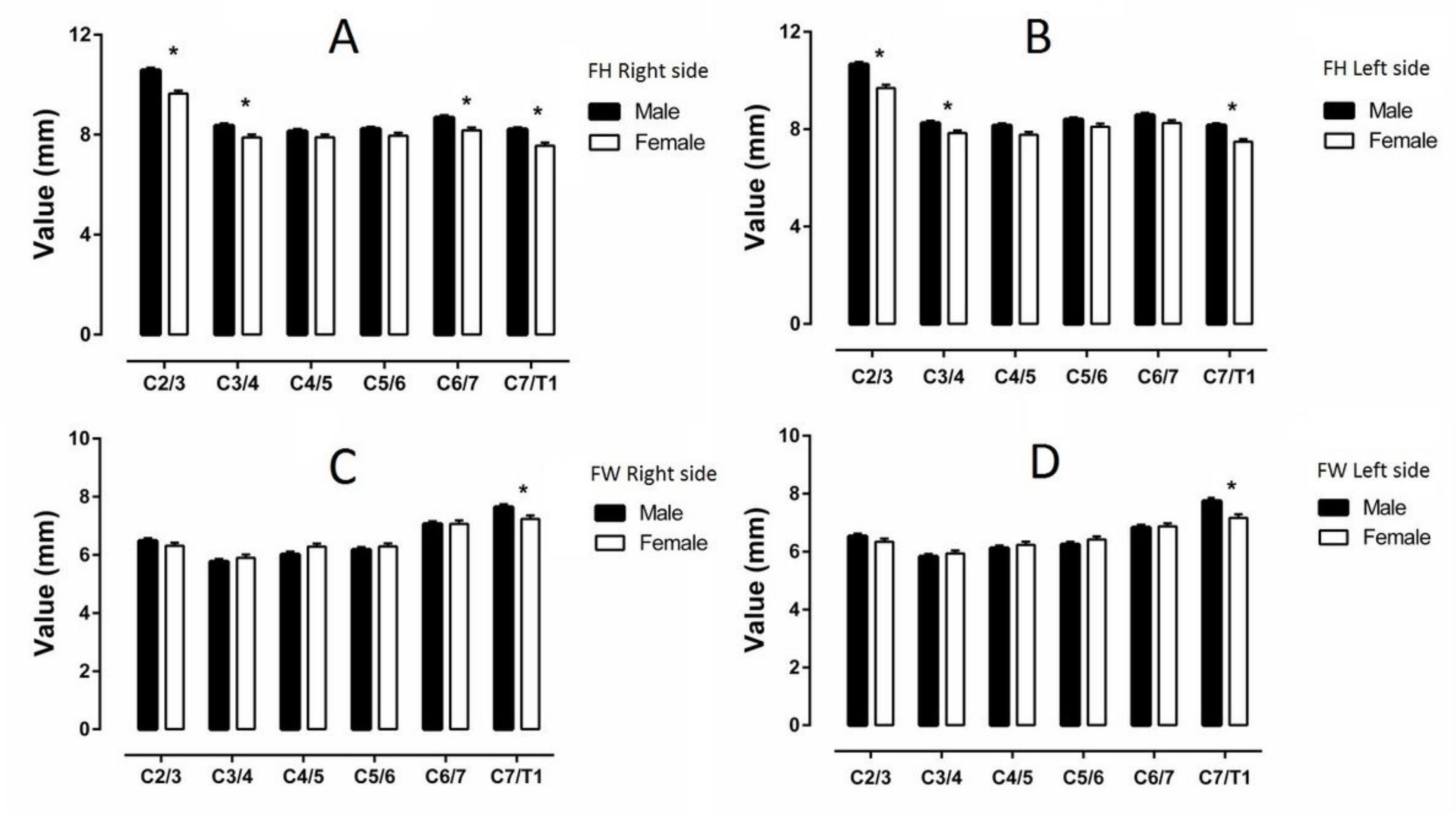

Figure 8

A: The mean values and standard deviations of FH at all measured intervertebral levels on the right side in males and females (all in mm). * denotes statistically significant difference (P<0.05). B: The mean values and standard deviations of FH at all measured intervertebral levels on the left side in males and females (all in mm). * denotes statistically significant difference (P<0.05). C: The mean values and standard deviations of FW at all measured intervertebral levels on the right side in males and females (all in mm). * denotes statistically significant difference (P<0.05). D: The mean values and standard deviations of FW at all measured intervertebral levels on the left side in males and females (all in mm). * denotes statistically significant difference (P<0.05).

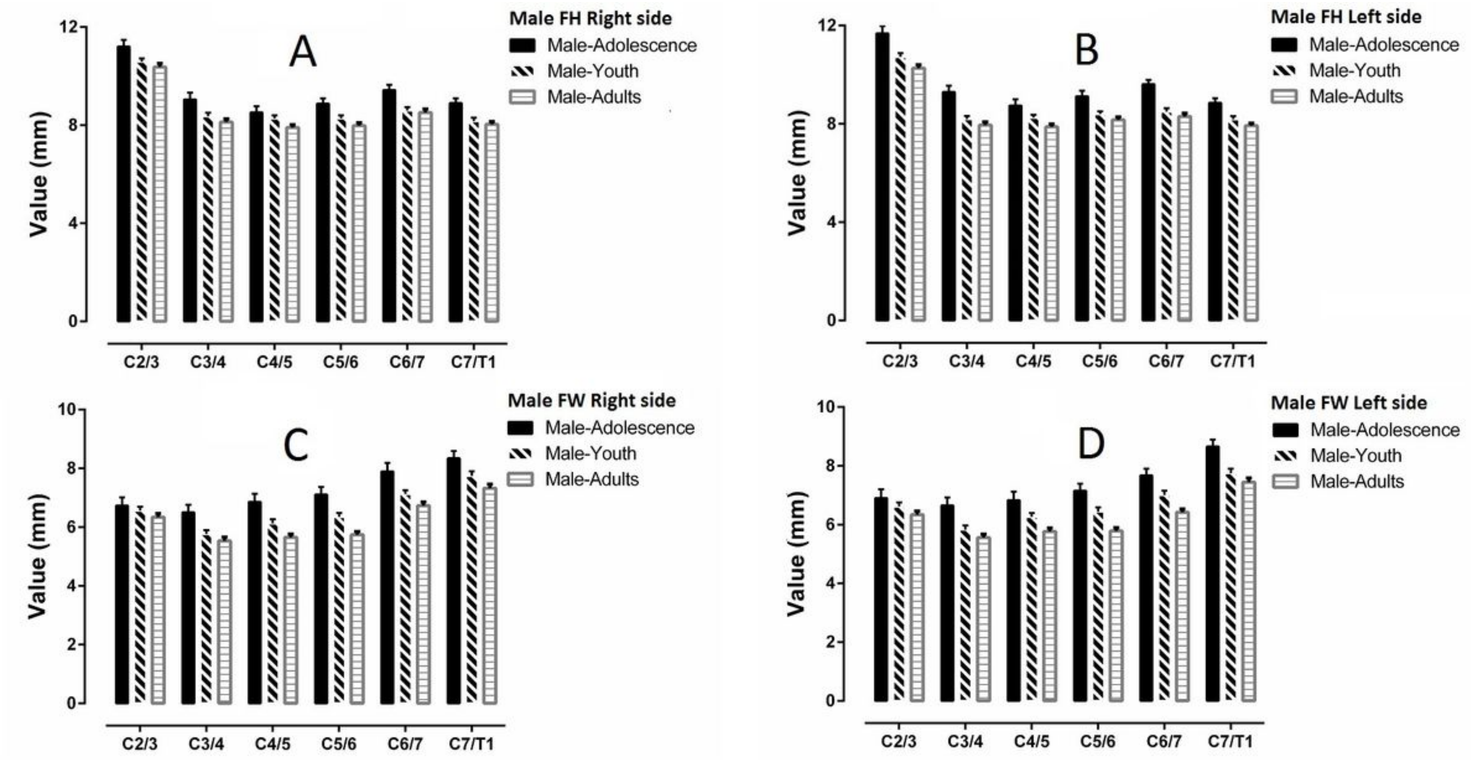

Figure 9

A: The mean values and standard deviations of FH at all measured intervertebral levels on the right side in adolescence, youth, and adult age groups in males (all in mm). B: The mean values and standard deviations of FH at all measured intervertebral levels on the left side in adolescence, youth, and adult age groups in males (all in mm). C: The mean values and standard deviations of FW at all measured intervertebral levels on the right side in adolescence, youth, and adult age groups in males (all in mm). D: The mean values and standard deviations of FW at all measured intervertebral levels on the left side in adolescence, youth, and adult age groups in males (all in mm).

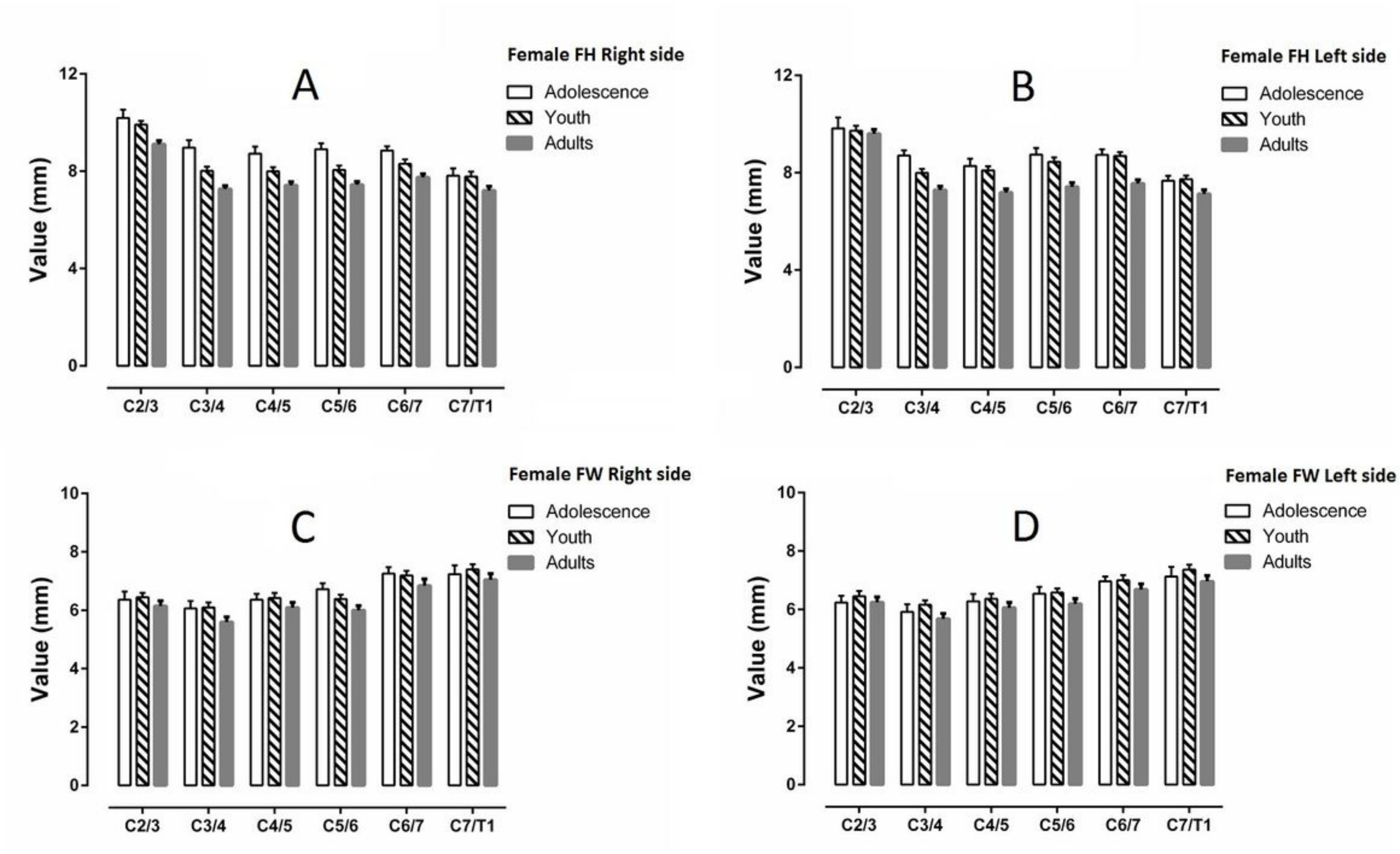

Figure 10

A: The mean values and standard deviations of FH at all measured intervertebral levels on the right side in adolescence, youth, and adult age groups in females (all in mm). B: The mean values and standard deviations of FH at all measured intervertebral levels on the left side in adolescence, youth, and adult age groups in females (all in mm). C: The mean values and standard deviations of FW at all measured intervertebral levels on the right side in adolescence, youth, and adult age groups in females (all in mm). D: The mean values and standard deviations of FW at all measured intervertebral levels on the left side in adolescence, youth, and adult age groups in females (all in mm).