The influence of age, anthropometrics and range of motion on the morphometry of the synovial folds of the lateral atlanto-axial joints: a pilot study

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Abstract The purpose of this study was to investigate the effect of age, anthropometrics and cervical range of motion upon synovial fold volume. Ten healthy female subjects aged 20–40 years were included in the study. Age, height, body mass, dimensions of the head and neck and cervical range of motion of each subject were measured. Magnetic resonance (MR) images of the cervical spine were acquired; the volume of the ventral and dorsal synovial folds of the right and the left lateral atlanto-axial joints was measured using seed growing and thresholding methods. Using Spearman's correlation coefficient, it was determined that there was no correlation between synovial fold volume and age. Synovial fold volume was positively correlated with subject height and neck length but negatively correlated with body mass, body mass index and the circumference of the head and neck. The relationship between synovial fold volume and range of cervical motion varied with the plane of movement. The ability to image the synovial folds of the lateral atlanto-axial joints using MR imaging to determine their normal morphology

provides the basis for investigating synovial fold pathology in patients with neck pain and headache.

Keywords Synovial folds · Atlanto-axial joints · Magnetic resonance imaging · Meniscoids · Whiplash

Introduction

Synovial folds, also known as meniscoids, menisci or synovial plicae, are formed by folds of the synovial membrane and are present in all joints of the cervical spine [33, 42]. They consist of a vascular central core of subintimal tissue covered by synovial intima [18]. At the lateral atlanto-axial joints, the synovial folds fill the ventral and dorsal articular recesses created by the incongruence of the convex hyaline articular cartilage surfaces [50]. Based on the presence of nerve fibres and the demonstration of substance-P-like and calcitonin gene-related protein-like immunoreactivity within the synovial folds, it is suggested that the synovial folds are potential sources of pain [19, 21, 26]. Pain originating from the synovial folds of the lateral atlanto-axial joints may manifest as neck pain, which might refer to the head, producing headache [1, 6].

A variety of functions are attributed to the synovial folds based upon extrapolations made from their gross morphology, disposition and histological composition. The synovial folds are believed to adapt themselves intimately to the contour of the joint space in all positions of the joint and act as 'passive space-fillers' that fill peripheral non-congruent parts of the joint in its neutral position but displace when the joint moves [2, 18, 20, 39, 42, 52]. It is not clear how the 'passive space-filling' role of the synovial folds affects physiological loading and motion of the spinal articulations [4] but it has been suggested that the synovial folds may

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protect and lubricate the articular surfaces, enhance joint congruity and stability or assist weight-bearing [2, 4, 39, 42].

A number of hypotheses have been proposed to explain the potential role of the synovial folds in the generation of neck pain and disability, including synovial fold entrapment [34, 35], synovial fold extrapment [3], intra-articular adhesions [28, 42], synovial fold rupture [3] and synovial fold impingement following whiplash injury [50, 53]. The major limitation of these theories is that they are solely based on the anatomy of the synovial folds reported at post-mortem. Due to differences in tissue properties between cadavers and living tissue, there is a need to study the synovial folds in vivo to ascertain their normal structure, function and potential clinical significance.

The purpose of the present study was to determine whether synovial fold morphometry is related to age, height, body mass and body mass index (BMI), the dimensions of the head and neck and cervical range of motion.

Materials and methods

Subjects

Ten healthy women aged between 20 and 40 years (mean 29.2 years, SD 4.69 years) with no contraindications to having a magnetic resonance (MR) scan volunteered for the study. Women aged 20–40 years were considered in the first instance because they tend to have a higher prevalence of symptoms following whiplash injury caused by motor vehicle trauma [24, 38, 59]. Subjects were excluded if they had a previous history of neck pain, injury or trauma; history of spinal surgery or spinal anomalies; had been previously diagnosed with a connective tissue disorder, neurologic disorder or inflammatory condition; were pregnant or breast-feeding. Subjects completed a questionnaire that included details of age, occupation, handedness, visual impairment and regular sports and recreational activities. The local research ethics committee reviewed and approved the study; all the subjects gave written informed consent prior to inclusion in the study.

MRI acquisition and measurements

A 1.5 Tesla scanner (Magnetom Symphony, Siemens, Erlangen, Germany) was used to acquire MR images of the cervical spine. A T2-weighted 3D-acquisition double-echo steady-state (DESS) water-excitation sequence in the sagittal plane (6.63 ms echo time (TE), 23.68 ms repetition time (TR), 64 slices, 1.50 mm slice thickness, no inter-slice gap, 256×192 acquisition matrix, 150 mm field of view, 25 degree flip angle, 6 min 32 s acquisition time) was performed. All scans were anonymised and stored as

DICOM (Digital Imaging and Communications in Medicine standard) format files on computer. Mimics 8.11 (Materialise, Leuven, Belgium) was used to quantify the volume of the synovial folds. The MR measure has been previously established [60]. In brief, regions of interest were manually traced from sagittal sections and used to reconstruct a 3D model of each synovial fold from which its volume was determined (Fig. 1). Three subjects (i.e. 12 synovial folds) were re-scanned 1 month after the initial scan and synovial fold volume quantified to determine the test–retest reliability of the method.

Measurement of anthropometrics and cervical range of motion

Standing height was measured using a stadiometer and body mass was measured with subjects standing barefoot on a beam balance scale. Three measurements were taken in succession and the average reading calculated. Body mass index [BMI = body mass (kg)/height squared (m^2)] was calculated from the average height and body mass measures. With the subject seated, the dimensions of the head and neck were measured by means of a flexible non-stretch measurement tape. All measurements were repeated three times and an average value for each dimension was calculated. Anterior neck length was measured from the gnathion to the suprasternal notch and the posterior neck length from the inion to the tip of the seventh cervical spinous process. The tape measure was placed on the skin to conform to the contours of the neck. Cranial circumference was measured from the median point on the glabella horizontally around the cranium

Fig. 1 Sagittal T2-weighted 3D-acquisition DESS water-excitation image showing the regions of interest of the ventral (V) and dorsal (D) synovial folds of the left lateral atlanto-axial joint (*lateral view*). Reproduced by kind permission of Lippincott Williams & Wilkins from Webb AL, Darekar AA, Sampson M, Rassoulian H (2009) Synovial folds of the lateral atlantoaxial joints: in vivo quantitative assessment using magnetic resonance imaging in healthy volunteers. Spine 34(19):E697–702

to the most prominent point on the back of the cranium. Neck circumference was measured around the cervical column at the level of the fifth cervical spinous process and just below the cricoid cartilage. The tape measure was held firmly against the skin, while allowing the subject to swallow comfortably. The cervical range of motion (CROM) instrument (Performance Attainment Associates, Lindstrom, MN, USA) was used to determine the active cervical range of motion (ROM) of each seated subject in all planes using the manufacturer's protocol [57]. The CROM instrument is a reliable and valid device for the measurement of cervical range of motion in clinical and experimental settings [55, 56]. Three repeat measurements were taken for each movement and the average was calculated.

Data analysis

Friedman's ANOVA was used to determine whether there was a difference in volume between the right ventral, right dorsal, left ventral and left dorsal synovial folds. Wilcoxon's signed-rank test was used for post hoc analysis with *Bonferroni correction*, so all effects are reported at a 0.0125 level of significance. Spearman's correlation coefficient (r_s) was used to determine the relationship between synovial fold volume and subject age, anthropometrics and cervical range of motion. To identify potential interactions between age, anthropometrics and cervical range of motion the following composite measures were calculated and the relationship between them analysed using Spearman's correlation coefficient (r_s): age, BMI, neck morphometry (ratio between neck circumference and average neck length) [49] and total cervical range of motion (flexion + extension + right lateral flexion + left lateral flexion + right rotation + left rotation) [12]. A probability level of $P = 0.05$ was set as the minimum criterion of statistical significance for correlation. The intra-class correlation coefficient [ICC (1,1)] was calculated to determine test-retest reliability. Statistical analysis was performed using SPSS 14.0 (SPSS Inc., Chicago, IL, USA).

Results

Ventral and dorsal synovial folds were identified in all the right and the left lateral atlanto-axial joints imaged. Forty synovial fold 3D models were reconstructed from the resulting MR images of the synovial folds of each joint. There was a significant difference in volume between the ventral and dorsal synovial folds of the right and the left lateral atlanto-axial joints ($\chi^2(3) = 8.76$, $P = 0.03$) (Fig. 2). The synovial fold volume of the right ventral and left ventral synovial folds was greater than the right dorsal and left dorsal synovial folds, respectively, but the

Fig. 2 Ventral and dorsal synovial fold volume (mm^3) at the *right* and *left* lateral atlanto-axial joints of all subjects ($n = 10$) showing the range of values and the median (*bar lines*)

differences were not significant ($Z = -2.09$, $P = 0.037$ and $Z = -1.58$, $P = 0.13$, respectively). The right ventral synovial fold volume was larger than the left ventral synovial fold volume but the difference was not significant ($Z = -1.89$, $P = 0.06$). The right dorsal synovial fold volume was greater than the left dorsal synovial fold volume but the difference did not quite reach significance ($Z = -2.40$, $P = 0.014$).

Nine subjects were right-handed and one subject was ambidextrous. There was a very weak correlation between subject age and synovial fold volume (Table 1). With the exception of the right ventral synovial folds, there was a strong positive correlation between subject height and synovial fold volume and a strong negative correlation between synovial fold volume and both body mass and BMI (Table 1). The synovial fold volume increased with increasing anterior and posterior neck length (Table 2). The correlation was moderate-strong for the dorsal synovial folds and weak-moderate for the ventral synovial folds. The synovial fold volume increased with decreasing neck circumference and head circumference (Table 2). The correlation between synovial fold volume and neck circumference was generally moderate. For head circumference, the relationship was strong for the synovial folds of the right articulations but weak for the synovial folds of the left articulations. The volume of the synovial folds was related to the range of cervical flexion and extension, with synovial fold volume generally increasing in association with a greater range of motion in the sagittal plane (Table 3). There was no clear relationship between the synovial fold volume and the range of lateral flexion

Table 1 Correlation between ventral and dorsal synovial fold volume (mm³) at the right and left lateral atlanto-axial joints with subject age (years), height (cm), body mass (kg) and BMI (kg/m²)

Spearman's r_s P value	Right ventral synovial fold	Right dorsal synovial fold	Left ventral synovial fold	Left dorsal synovial fold
Age (years)	−0.15 $P = 0.67$	−0.18 $P = 0.62$	−0.25 $P = 0.48$	0.10 $P = 0.77$
Height (cm)	0.27 $P = 0.28$	0.64 $P = 0.04$	0.65 $P = 0.04$	0.68 $P = 0.03$
Body mass (kg)	−0.24 $P = 0.33$	−0.64 $P = 0.048$	−0.58 $P = 0.08$	−0.73 $P = 0.02$
BMI (kg/m ²)	−0.29 $P = 0.25$	−0.69 $P = 0.03$	−0.59 $P = 0.07$	−0.75 $P = 0.01$

Table 2 Correlation between ventral and dorsal synovial fold volume (mm³) at the right and left lateral atlanto-axial joints with the dimensions of the head and neck (cm)

Spearman's r_s P value	Right ventral synovial fold	Right dorsal synovial fold	Left ventral synovial fold	Left dorsal synovial fold
Anterior neck length (cm)	0.18 $P = 0.61$	0.49 $P = 0.15$	0.43 $P = 0.21$	0.56 $P = 0.10$
Posterior neck length (cm)	0.22 $P = 0.53$	0.49 $P = 0.15$	0.16 $P = 0.65$	0.77 $P = 0.01$
Neck circumference (cm)	−0.38 $P = 0.28$	−0.54 $P = 0.11$	−0.59 $P = 0.07$	−0.53 $P = 0.12$
Head circumference (cm)	−0.61 $P = 0.06$	−0.62 $P = 0.05$	−0.33 $P = 0.35$	−0.27 $P = 0.45$

Table 3 Correlation between ventral and dorsal synovial fold volume (mm³) at the right and left lateral atlanto-axial joints with cervical range of motion (degrees)

Spearman's r_s P value	Right ventral synovial fold	Right dorsal synovial fold	Left ventral synovial fold	Left dorsal synovial fold
Flexion (°)	0.13 $P = 0.74$	0.39 $P = 0.27$	0.56 $P = 0.09$	0.41 $P = 0.24$
Extension (°)	0.25 $P = 0.49$	0.59 $P = 0.07$	0.38 $P = 0.28$	0.79 $P = 0.01$
Right lateral flexion (°)	0.13 $P = 0.74$	0.13 $P = 0.73$	−0.20 $P = 0.58$	0.32 $P = 0.37$
Left lateral flexion (°)	0.06 $P = 0.87$	0.21 $P = 0.55$	−0.03 $P = 0.93$	0.23 $P = 0.53$
Right rotation (°)	0.15 $P = 0.68$	0.18 $P = 0.63$	0.35 $P = 0.33$	0.29 $P = 0.43$
Left rotation (°)	0.44 $P = 0.20$	0.58 $P = 0.08$	0.69 $P = 0.03$	0.43 $P = 0.22$

(Table 3). The synovial fold volume increased in association with increasing range of rotation (Table 3) with the strength of relationship being greater for left rotation as compared to right rotation.

There was a very strong correlation between BMI and neck morphometry and a strong correlation between total cervical range of motion and both BMI and neck morphometry (Table 4). A weak-moderate correlation was evident between age and the three composite measures of BMI, neck morphometry and total cervical range of motion (Table 4).

The test–retest reliability for the measurement of the synovial fold volume was excellent (ICC 0.99).

Discussion

In agreement with Webb et al. [60] the ventral synovial folds were larger than the dorsal synovial folds and the right ventral and dorsal synovial folds were larger than the left ventral and dorsal synovial folds; however, in the

Table 4 Correlation between age (years), body mass index (BMI) (kg/m²), neck morphometry (cm) and total cervical range of motion (degrees)

Spearman's r_s P value	Age (years)	BMI (kg/m ²)	Neck morphometry (cm)
BMI (kg/m ²)	0.55 $P = 0.10$		
Neck morphometry (cm)	−0.30 $P = 0.40$	−0.94 $P = 0.000$	
Total ROM (degrees)	−0.44 $P = 0.21$	−0.72 $P = 0.02$	0.62 $P = 0.05$

present study these did not reach significance. All subjects were right-hand dominant with one being ambidextrous; therefore, side-to-side differences might be the result of a dominance effect. Further studies including left-hand dominant subjects are needed to clarify this issue. The degree of an individual's sagittal and coronal head tilt [48] might also influence the size of the ventral and dorsal synovial folds and right and left synovial folds, respectively. Based upon observations from cadaver studies, it is suggested that the morphology of the synovial folds changes in association with increasing age and/or articular degeneration [15, 25, 33, 51, 62]. In agreement with Friedrich et al. [17] and Webb et al. [60], neither of these age-related observations was verified by the results of the present study.

The size of the synovial folds was related to subject anthropometry. The dimensions of the subject's body as a whole, rather than the regional dimensions of the head and neck, were strongly related to synovial fold volume. The larger synovial fold volume was associated with taller subjects and with those who weighed less and had a lower BMI. This is in contrast to the dimensions of the articular facets, spinal cord and some cervical muscles, which typically increase in size in association with greater body size [10, 31, 41, 61]. Although, in the main, synovial fold volume was not as strongly related to the dimensions of the head and neck, there was a general trend for synovial fold volume to increase with increasing neck length and to increase with decreasing head and neck circumference, i.e. larger synovial folds were generally associated with long slender necks and smaller heads.

At low-speed motor vehicle collisions, occupants with smaller neck circumference and lower BMI experience greater head acceleration as compared to occupants with a larger neck circumference and greater BMI, respectively [23, 37]. Freeman et al. [16] found an increased risk of association between BMI and chronic neck pain following a motor vehicle collision but did not find an increased risk in the female population. Thus Freeman et al. [16] have

suggested that body mass and neck circumference rather than female gender [24] are most likely to result in the development of neck pain following a whiplash trauma. Females generally have smaller necks and less body mass as compared to males, which may explain why this relationship is thought to have been attributed to gender [16, 22]. The finding in the present study that taller individuals with less body mass and lower BMI, and longer more slender necks, had larger synovial folds is of potential relevance to the understanding of the biomechanics and pathoanatomy of a whiplash injury. Larger synovial folds may be more vulnerable to being pinched and bruised between the articular surfaces following the application of a traumatic force. Contusions of the synovial folds and occult fractures of the articular processes are two of the most common injuries that affect the cervical articulations at post-mortem following motor vehicle trauma [29, 53]. Taller individuals with less body mass, lower BMI and long slender necks that have larger synovial folds may be more prone to bruising of the synovial folds following whiplash trauma but less vulnerable to damage affecting the hyaline articular cartilage and articular facets. In contrast, shorter individuals with greater body mass and BMI and shorter thicker necks that have smaller synovial folds may be more prone to articular cartilage and subchondral bone damage following motor vehicle trauma.

The function of the synovial folds is not known. In the present study, larger lateral atlanto-axial synovial folds were typically associated with a greater range of flexion, extension and rotation but not lateral flexion. This is in agreement with the atlanto-axial joints having the greatest range of rotation in the cervical spine [8, 45, 46] and the observation that the synovial folds of the lateral atlanto-axial joints are larger than the synovial folds of the cervical zygapophysial joints [62]. Furthermore, the lateral atlanto-axial joints have a moderate range of flexion and extension and a small range of segmental lateral flexion [45]. The measurement of cervical ROM is interpreted as an indication of the state of the anatomic structures within or around the joints [58] and the function of the cervical spine is evaluated by assessing its ROM. The presence of a relationship between cervical ROM and the size of the synovial folds would suggest that the synovial folds are involved in the facilitation of mobility rather than stability.

Cervical range of motion forms an integral component of spinal evaluation and is the principal criterion in the quantification of musculoskeletal impairment [40, 43, 56]. In patients with whiplash-associated disorder, all planes of motion are reduced with the sagittal plane movements the most affected [5, 7, 30, 47]. Patients with headache also demonstrate decreased motion [13, 44]. The cause of the reduced range of motion associated with neck pain and headache is not known but suggested reasons include

mechanical changes in the tissues or pain inhibition [5, 30]. Because the measurement of cervical range of motion is interpreted as an indication of the state of the anatomic structures within or around the joint complex, abnormal results may indicate abnormalities affecting the cervical articular structures [58]. It is currently not known as to what these abnormalities might be; however, injuries to the synovial folds in patients with neck pain and/or headache might be related to the reduction in cervical range of motion observed in these patient groups.

In principle, multiple regression analysis could have been used to investigate the relationship between synovial fold volume (outcome variable) and age, anthropometrics and cervical range of motion (predictor variables) and in addition assess the potential for interactions between the predictor variables. However, the present study was a pilot study with a small number of subjects. Undertaking multiple regression analysis with a small sample size is not reliable and a sample size of at least 10–15 participants per predictor variable is recommended [14]. Although it would be possible to tease out potential relationships, to do so in a reliable way would require considerably more participants. Despite this, it was prudent to explore potential interactions between composite measures of age, body dimensions, neck dimensions and cervical range of motion as a first step in looking at such relationships. The very strong correlation between BMI and neck morphometry is of particular interest as a high level of collinearity threatens the validity of multiple regression analyses making it difficult to assess the individual importance of a predictor, increasing the probability of a type II error and producing predictor equations that are not reliable. A larger study is planned for the future as these relationships require further careful consideration. The results of the present study will be used to select suitable predictor variables and the method in which these variables are entered into the regression model.

To date, it has not been possible to visualise specific morphological changes using standard cervical MR imaging in patients with neck pain [32, 43]. Recent MR studies have described the possible presence of visible changes to muscles and ligaments in neck pain patients after whiplash [9, 36]. The reliability of quantitative methods [9, 11] appears to be superior to that of qualitative methods [36]. The reliability of the quantitative MR measure of synovial fold volume used in the present study has been previously reported [60]. The measurement method proved to have high levels of intra-observer and inter-observer reliability, ICC 0.99 and ICC 0.82, respectively [60]. In the present study, the reliability of the method for measuring synovial fold volume was tested further by examining the consistency of synovial fold dimensions that were imaged and measured on different occasions (test–retest reliability). The test–retest reliability of the method was excellent (ICC

0.99) and consistent with that reported in previous studies [9, 11, 27, 54].

Conclusion

The results of the present study go some way toward accounting for the variability observed in the dimensions of the synovial folds of the lateral atlanto-axial joints. For future studies, the results highlight the importance of considering normal variations in synovial fold size for optimal discrimination between asymptomatic individuals and those suffering from neck pain and/or headache. This preliminary work provides a basis for further study of a symptomatic population to determine the presence and significance of changes in the dimensions of the synovial folds in patients with neck pain and disorders of the cervical spine.

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References

1. Bogduk N (1992) The anatomical basis for cervicogenic headache. *J Manipulative Physiol Ther* 15:67–70
2. Bogduk N, Engel R (1984) The menisci of the lumbar zygapophyseal joints. A review of their anatomy and clinical significance. *Spine* 9:454–460
3. Bogduk N, Jull G (1985) The theoretical pathology of acute locked back: a basis for manipulative therapy. *Man Med* 1:78–82
4. Chang H, Found EM, Clark CR, Goel VK, Gang CS (1992) Meniscus-like synovial fold in the atlanto-axial (C1–C2) joint. *J Spinal Disord* 5:227–231
5. Dall'Alba PT, Sterling MM, Treleaven JM, Edwards SL, Jull GA (2001) Cervical range of motion discriminates between asymptomatic persons and those with whiplash. *Spine* 26:2090–2094
6. Dreyfuss P, Michaelsen M, Fletcher D (1994) Atlanto-occipital and lateral atlanto-axial joint pain patterns. *Spine* 19:1125–1131
7. Dvir Z, Gal-Eshel N, Shamir B, Prushansky T, Pevzner E, Peretz C (2006) Cervical motion in patients with chronic disorders of the cervical spine: a reproducibility study. *Spine* 31:E394–E399
8. Dvorak J, Panjabi M, Gerber M, Wichmann W (1987) CT-functional diagnostics of the rotatory instability of upper cervical spine. 1. An experimental study on cadavers. *Spine* 12:197–205
9. Elliott JM, Jull GA, Noteboom JT, Darnell R, Galloway G, Gibbon WW (2006) Fatty infiltration in the cervical extensor muscles in persistent whiplash-associated disorders: a magnetic resonance imaging analysis. *Spine* 31:E847–E855
10. Elliott JM, Jull GA, Noteboom JT, Durbridge GL, Gibbon WW (2007) Magnetic resonance imaging study of cross-sectional area of the cervical extensor musculature in an asymptomatic cohort. *Clin Anat* 20:35–40
11. Elliott JM, Jull GA, Noteboom JT, Galloway G (2008) MRI study of the cross-sectional area for the cervical extensor musculature

- in patients with persistent whiplash associated disorders (WAD). *Man Ther* 13:258–265
12. Elliott J, Sterling M, Noteboom JT, Galloway G, Jull G (2009) The clinical presentation of chronic whiplash and the relationship to findings of MRI fatty infiltrates in the cervical extensor musculature: a preliminary investigation. *Eur Spine J* 18:1371–1378
 13. Fernandez-de-las-Penas C, Alonso-Blanco C, Cuadrado ML, Pareja JA (2007) Neck mobility and forward head posture are not related to headache parameters in chronic tension-type headache. *Cephalalgia* 27:158–164
 14. Field A (2005) *Discovering statistics using SPSS*. SAGE Publications, London
 15. Fletcher G, Haughton VM, Ho KC, Yu SW (1990) Age-related changes in the cervical facet joints: studies with cryomicrotomy, MR, and CT. *AJR Am J Roentgenol* 154:817–820
 16. Freeman MD, Croft AC, Rossignol AM, Centeno CJ, Elkins WL (2006) Chronic neck pain and whiplash: a case-control study of the relationship between acute whiplash injuries and chronic neck pain. *Pain Res Manag* 11:79–83
 17. Friedrich KM, Reiter G, Pretterklieber ML, Pinker K, Friedrich M, Trattinig S, Salomonowitz E (2008) Reference data for in vivo magnetic resonance imaging properties of meniscoids in the cervical zygapophyseal joints. *Spine* 33:E778–E783
 18. Giles LG (1986) Lumbo-sacral and cervical zygapophyseal joint inclusions. *Man Med* 2:89–92
 19. Giles LG, Harvey AR (1987) Immunohistochemical demonstration of nociceptors in the capsule and synovial folds of human zygapophyseal joints. *Br J Rheumatol* 26:362–364
 20. Giles LG, Taylor JR (1982) Intra-articular synovial protrusions in the lower lumbar apophyseal joints. *Bull Hosp Jt Dis Orthop Inst* 42:248–255
 21. Giles LG, Taylor JR (1987) Innervation of lumbar zygapophyseal joint synovial folds. *Acta Orthop Scand* 58:43–46
 22. Harty JA, Quinlan JF, Kennedy JG, Walsh M, O'Byrne JM (2004) Anthropometrical analysis of cervical spine injuries. *Injury* 35:249–252
 23. Hell W, Schick S, Langwieder K, Zellmer H (2002) Biomechanics of cervical spine injuries in rear end car impacts: influence of car seats and possible evaluation criteria. *Traffic Inj Prev* 3:127–140
 24. Holm LW, Carroll LJ, Cassidy JD, Hogg-Johnson S, Cote P, Guzman J, Peloso PM, Nordin M, Hurwitz EL, van der Velde G, Carragee EJ, Haldeman S (2008) The burden and determinants of neck pain in whiplash-associated disorders after traffic collisions. Results of the bone and joint decade 2000–2010 task force on neck pain and its associated disorders. *Eur Spine J* 17:S52–S59
 25. Inami S, Kaneoka K, Hayashi K, Ochiai N (2000) Types of synovial fold in the cervical facet joint. *J Orthop Sci* 5:475–480
 26. Inami S, Shiga T, Tsujino A, Yabuki T, Okado N, Ochiai N (2001) Immunohistochemical demonstration of nerve fibers in the synovial fold of the human cervical facet joint. *J Orthop Res* 19:593–596
 27. Inglis D, Pui M, Ioannidis G, Beattie K, Boulos P, Adachi JD, Webber CE, Eckstein F (2007) Accuracy and test-retest precision of quantitative cartilage morphology on a 1.0 T peripheral magnetic resonance imaging system. *Osteoarthritis Cartilage* 15:110–115
 28. Jones TR, James JE, Adams JW, Garcia J, Walker SL, Ellis JP (1989) Lumbar zygapophyseal joint meniscoids: evidence of their role in chronic intersegmental hypomobility. *J Manipulative Physiol Ther* 12:374–385
 29. Jonsson H Jr, Bring G, Rauschnig W, Sahlstedt B (1991) Hidden cervical spine injuries in traffic accident victims with skull fractures. *J Spinal Disord* 4:251–263
 30. Kaale BR, Krakenes J, Albrektsen G, Wester K (2007) Active range of motion as an indicator for ligament and membrane lesions in the upper cervical spine after a whiplash trauma. *J Neurotrauma* 24:713–721
 31. Karacan I, Aydin T, Sahin Z, Cidem M, Koyuncu H, Aktas I, Uludag M (2004) Facet angles in lumbar disc herniation: their relation to anthropometric features. *Spine* 29:1132–1136
 32. Kongsted A, Sorensen JS, Andersen H, Keseler B, Jensen TS, Bendix T (2008) Are early MRI findings correlated with long-lasting symptoms following whiplash injury? A prospective trial with 1-year follow-up. *Eur Spine J* 17:996–1005
 33. Kos J, Hert J, Sevcik P (2002) Meniscoids of the intervertebral joints. *Acta Chir Orthop Traumatol Cech* 69:149–157
 34. Kos J, Wolf J (1972) Die “menisci” der zwischenwirbelgelenke und ihre mogliche rolle bei wirbelblockierung. *Man Med* 10:105–114
 35. Kos J, Wolf J (1976) Intervertebral menisci and their possible role in intervertebral blockage. *Bull Sports Med Sect* 1:8–9, 14
 36. Krakenes J, Kaale BR, Moen G, Nordli H, Gilhus NE, Rorvik J (2002) MRI assessment of the alar ligaments in the late stage of whiplash injury—a study of structural abnormalities and observer agreement. *Neuroradiology* 44:617–624
 37. Kroonenberg A, Philippens H, Capon J, Wismans J, Hell W, Langweider K (1998) Human head-neck response during low-speed rear end impacts. In: *Proceedings of the 42nd Stapp Car Crash Conference*
 38. Larsen LB, Holm R (2000) Prolonged neck pain following automobile accidents. Gender and age related risk calculated on basis of data from an emergency department. *Ugeskr Laeger* 162:178–181
 39. Lewin T, Moffett B, Viidik A (1962) The morphology of the lumbar synovial intervertebral joints. *Acta Morphol Neerl Scand* 4:299–319
 40. Mannion AF, Klein GN, Dvorak J, Lanz C (2000) Range of global motion of the cervical spine: intraindividual reliability and the influence of measurement device. *Eur Spine J* 9:379–385
 41. Masharawi Y, Rothschild B, Salame K, Dar G, Peleg S, Herskovitz I (2005) Facet tropism and interfacet shape in the thoracolumbar vertebrae: characterization and biomechanical interpretation. *Spine* 30:E281–E292
 42. Mercer S, Bogduk N (1993) Intra-articular inclusions of the cervical synovial joints. *Br J Rheumatol* 32:705–710
 43. Nordin M, Carragee EJ, Hogg-Johnson S, Weiner SS, Hurwitz EL, Peloso PM, Guzman J, van der Velde G, Carroll LJ, Holm LW, Cote P, Cassidy JD, Haldeman S (2008) Assessment of neck pain and its associated disorders. Results of the bone and joint decade 2000–2010 task force on neck pain and its associated disorders. *Eur Spine J* 17:S101–S122
 44. Ogince M, Hall T, Robinson K, Blackmore AM (2007) The diagnostic validity of the cervical flexion-rotation test in C1/2-related cervicogenic headache. *Man Ther* 12:256–262
 45. Panjabi M, Dvorak J, Duranceau J, Yamamoto I, Gerger M, Rauschnig W, Bueff HU (1988) Three-dimension movements of the upper cervical spine. *Spine* 13:726–730
 46. Penning L, Wilmink JT (1987) Rotation of the cervical spine. A CT study in normal subjects. *Spine* 12:732–738
 47. Prushansky T, Pevzner E, Gordon C, Dvir Z (2006) Performance of cervical motion in chronic whiplash patients and healthy subjects: the case of atypical patients. *Spine* 31:37–43
 48. Raine S, Twomey LT (1997) Head and shoulder posture variations in 160 asymptomatic women and men. *Arch Phys Med Rehabil* 78:1215–1223
 49. Reynolds J, Marsh D, Koller H, Zenenr J, Bannister G (2009) Cervical range of movement in relation to neck dimension. *Eur Spine J* 18:863–868
 50. Schonstrom N, Twomey L, Taylor J (1993) The lateral atlanto-axial joints and their synovial folds: an in vitro study of soft tissue injuries and fractures. *J Trauma* 35:886–892

51. Tang XY, Liu LJ, Yang HJ, Peng MX, Liao SH (2007) Anatomic study of the synovial folds of the occipito-atlanto-axial joints. *Clin Anat* 20:376–381
52. Taylor JR, McCormick CC (1991) Lumbar facet joint fat pads: their normal anatomy and their appearance when enlarged. *Neuroradiology* 33:38–42
53. Taylor JR, Taylor MM (1996) Cervical spine injuries: an autopsy study of 109 blunt injuries. *J Musculoskelet Pain* 4:61–79
54. Tench CR, Morgan PS, Constantinescu CS (2005) Measurement of cervical spinal cord cross-sectional area by MRI using edge detection and partial volume correction. *J Magn Reson Imaging* 21:197–203
55. Tousignant M, Duclos E, Lafleche S, Mayer A, Tousignant-Laflamme Y, Brosseau L, O'Sullivan JP (2002) Validity study for the cervical range of motion device used for lateral flexion in patients with neck pain. *Spine* 27:812–817
56. Tousignant M, Semesters C, Breton AM, Breton E, Corriveau H (2006) Criterion validity study of the cervical range of motion (CROM) device for rotational range of motion on healthy adults. *J Orthop Sports Phys Ther* 36:242–248
57. University Of Minnesota (1988) CROM procedure manual. Procedure for measuring neck motion with the CROM. University of Minnesota, Minnesota
58. Walmsley RP, Kimber P, Culham E (1996) The effect of initial head position on active cervical axial rotation range of motion in two age populations. *Spine* 21:2435–2442
59. Walton DM, Pretty J, MacDermid JC, Teasell RW (2009) Risk factors for persistent problems following whiplash injury: results of a systematic review and meta-analysis. *J Orthop Sports Phys Ther* 39:334–350
60. Webb AL, Darekar AA, Sampson M, Rassoulian H (2009) Synovial folds of the lateral atlantoaxial joints: in vivo quantitative assessment using magnetic resonance imaging in healthy volunteers. *Spine* 34:E697–E702
61. Yanase M, Matsuyama Y, Hirose K, Takagi H, Yamada M, Iwata H, Ishiguro N (2006) Measurement of the cervical spinal cord volume on MRI. *J Spinal Disord Tech* 19:125–129
62. Yu SW, Sether L, Haughton VM (1987) Facet joint menisci of the cervical spine: correlative MR imaging and cryomicrotomy study. *Radiology* 164:79–82