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Lateral atlantoaxial joint meniscoid volume in individuals with whiplash associated disorder: a case-control study

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Abstract:

Background: Lateral atlantoaxial (LAA) joints are established sources of nociceptive input in chronic whiplash associated disorder (WAD). These joints contain intra-articular meniscoids that may be damaged in whiplash trauma. LAA joint meniscoid morphology has not been investigated comprehensively in a chronic WAD population, and it is unclear whether morphological differences exist compared to a pain-free population.

Objectives: This study examined LAA joint meniscoid volume in individuals with chronic WAD who report pain in a distribution consistent with LAA joint pain.

Design: Case-control study.

Method: Fourteen individuals with chronic WAD with pain in an LAA joint distribution (mean [SD] age 38.1 [10.8] years; six female) and 14 age- and sex-matched pain-free controls (38.0 [10.5] years) underwent cervical spine magnetic resonance imaging. LAA joint images were inspected for meniscoids; meniscoid volume was calculated in mm³ and as a percentage of articular cavity volume. Symptom duration, location and intensity were recorded. Data were analysed using paired t-tests, Wilcoxon signed-rank testing, Spearman's rank testing, linear and logistic regression ($\alpha < 0.05$).

Results: Ventral and dorsal meniscoids (n = 112) were found in each LAA joint. Greater dorsal meniscoid volume as a percentage of articular cavity volume was associated with higher pain intensity (odds ratio 1.48, p = 0.03; likelihood ratio test chi-square₂ = 6.64, p = 0.04), however no significant differences existed between meniscoid volumes of WAD and control participants.

Conclusions: Findings indicate a potential link between dorsal LAA joint meniscoid volume and pain, suggesting larger meniscoid size may have pathoanatomical significance in WAD.

Keywords: whiplash; atlanto-axial joint; meniscoid; synovial fold; magnetic resonance imaging; neck pain; cervical spine

Introduction

Whiplash associated disorder (WAD) poses a substantial challenge to healthcare providers globally. An estimated one in two people who sustain a whiplash injury do not make a complete recovery (Carroll et al., 2008) and approximately 30% remain moderately to severely disabled by the condition (Sterling et al., 2006). Appreciation of the mechanisms that underpin chronic WAD has progressed in recent decades, and it appears

that musculoskeletal, neurological and psychological factors are potentially involved in this condition (Sterling et al., 2011).

Substantial evidence exists regarding the contribution of cervical spine joints to chronic WAD symptoms (Bogduk, 2011). A series of landmark studies employing diagnostic cervical medial branch nerve blocks established cervical zygapophyseal joints as sources of nociceptive input in approximately 50% of individuals with chronic WAD (Bogduk, 2011; Lord et al., 1996). Lateral atlantoaxial (LAA) joints have also been shown to be symptomatic in individuals both with chronic WAD and idiopathic neck pain (Aprill et al., 2002; Bogduk & Marsland, 1988; Cooper et al., 2007), with resulting pain perceived in the posterior upper cervical spine, sub-occipital region, and throughout the cranial region, confirming the LAA joints as potential sources of nociceptive input.

Within the LAA joints lie meniscoids, folds of synovial membrane that project between the articular surfaces (Farrell et al., 2016c; Webb et al., 2012). LAA joint meniscoids are composed of adipose tissue, fibrous tissue, or a combination of both, and are lined with synovial membrane (Farrell et al., 2016c). Immunohistochemical studies indicate potential for these structures to be innervated, suggesting they may be a source of nociceptive input (Farrell et al., 2016b; Inami et al., 2001). Biomechanical investigation has demonstrated that during whiplash loading LAA joints are vulnerable to hyperflexion, in such a manner as to exceed physiological limits and potentially lead to tissue injury (Grauer et al., 1997). Further to this, Schonstrom et al. (1993) and Taylor and Taylor (1996) have described bruising of LAA joint meniscoids in the cervical spines of victims of fatal motor vehicle collision (MVCs), inferring meniscoids to be vulnerable to damage in trauma.

LAA joint meniscoid morphology has been assessed in healthy volunteers by measuring meniscoid volume (Webb et al., 2011; Webb et al., 2009) using magnetic resonance imaging (MRI). Although no previously published reports exist documenting injury to cervical spine meniscoids in a living sample following whiplash, Farrell et al. (2016a) reported decreased anterior-posterior length of LAA joint meniscoids in individuals with chronic WAD compared with matched pain-free volunteers in a recent study using MRI. These authors however did not report details of participant clinical presentation, and it is therefore unclear how these findings relate to individuals' symptoms.

The LAA joints are thus a documented source of nociceptive input in chronic WAD, however it is unclear what role LAA meniscoids may play in WAD symptoms. The LAA joint meniscoids may be damaged during a whiplash injury, and because they have potential to be innervated, they could therefore contribute to patient symptoms in WAD (Farrell et al., 2017). Should these structures be damaged in a whiplash injury, it is feasible that their morphology may alter (Farrell et al., 2016a), which has implications for understanding the pathoanatomical underpinnings of chronic WAD. The purpose of this exploratory study was to investigate the volume of LAA joint meniscoids in individuals with chronic WAD who report pain in a distribution consistent with LAA joint pain, compared to pain-free participants in order to determine whether LAA joint meniscoid morphology is altered in chronic WAD.

Method

Ethical Approval Statement

Ethical approval was granted by the applicable institutional human research ethics committees (Hunter New England Local Health District Human Research Ethics Committee [Ref. 13/09/18/4.09] and The University of Newcastle Human Research Ethics Committee [Ref. H-2014-0018]). Each participant gave written informed consent prior to participating in the study.

Participants

Participants were recruited using posters displayed at a university campus, as well as in physiotherapy and medical clinics in the city of Newcastle in NSW, Australia. A research volunteer database of the Hunter Medical Research Institute (Newcastle, NSW, Australia) was also utilised to recruit participants. People interested in participating in the study contacted researchers by telephone or email, and were screened for eligibility by a physiotherapist researcher. Participants were recruited for two study groups. The first (WAD) group consisted of individuals with chronic WAD reporting neck pain or headache symptoms in a distribution consistent with LAA joint pain maps established in prior studies (Aprill et al., 2002; Cooper et al., 2007; Dreyfuss et al., 1994). The second group (control) consisted of pain-free volunteers age- and sex-matched to individuals in the WAD group. Recruitment for this project occurred over nine months between late 2014 and mid-2015.

For the WAD group, inclusion criteria consisted of Grade II WAD, as defined by The Quebec Task Force on Whiplash-Associated Disorders (Spitzer et al., 1995), that is, neck pain associated with decreased cervical range of motion and tenderness on palpation, which included pain in a distribution consistent with the pain maps described by previous authors (Aprill et al., 2002; Cooper et al., 2007; Dreyfuss et al., 1994). Briefly, these studies used diagnostic blocks of LAA joints in neck pain and headache patients (Aprill et al., 2002; Cooper et al., 2007) or intra-articular noxious injections to experimentally induce temporary LAA joint pain (Dreyfuss et al., 1994), with findings indicating that pain arising from the LAA joints can be perceived in the posterior upper cervical spine, sub-occipital region, and throughout the cranial region (Appendix A). Onset of this pain after a MVC or similar cervical spine trauma was necessary for eligibility for this group, as was greater than three months' duration of symptoms. For the control group, participants were eligible for inclusion if they matched the age ($\pm$ 1 year) and sex of a participant in the WAD group, and had no history of cervical spine trauma, MVC, neck pain lasting greater than 2 weeks' duration, or recurrent headaches.

For both groups, exclusion criteria comprised history of spinal fracture or specific pathology (such as malignancy or radiculopathy), previous cervical spine surgery, congenital cervical abnormalities, inflammatory or connective tissue pathologies, as well as contraindications related to MRI safety (such as cardiac pacemaker, aneurysm clip).

MRI Protocol

Each participant underwent cervical spine MRI, using a protocol based on that described by Friedrich et al. (2008) in a Siemens Magnetom Skyra 3.0 Tesla unit (Siemens AG, Munich, Germany) with a 20-channel head and neck coil. Participants were positioned in supine with the cervical spine in neutral position, as determined on inspection by a radiographer. Foam wedges were used to support participants in this position and limit movement during scanning.

The sequence utilised was a T1-weighted volumetric inter-polated breath-hold examination (T1 VIBE) sequence with fat suppression. This sequence was employed to permit clear visualisation of the LAA joint meniscoids, which may be composed of adipose tissue, fibrous tissue, or a combination of adipose and fibrous tissue. On a T1 VIBE sequence with fat suppression, adipose tissue and fibrous tissue are both hypointense, and this sequence therefore facilitates delineation of meniscoid boundaries against the articular cavity. Fat suppression

also serves to address potential for chemical shift artefact (Bley et al., 2010; Delfaut et al., 1999), which could have affected visualisation of meniscoid anatomical borders through misregistration of fat and water pixels, such as that of meniscoids and synovial fluid, respectively. Breath holds were not performed during scanning. Image acquisition was undertaken in the sagittal plane, as LAA joint meniscoids are located at the ventral and dorsal aspects of the joint, and as such sagittal plane imaging allows visualisation of these structures in cross-section (Mercer & Bogduk, 1993). The sequence was encoded in an anterior-to-posterior direction, with a slice thickness of 0.6 mm (20% slice oversampling) with 120 slices per slab (90% slice resolution), a 200 x 200 mm² field of view and a 320 x 288 matrix, to produce an isotropic resolution of 0.6 x 0.6 x 0.6 mm³. Repetition time, echo time, flip angle and bandwidth were 10.8 ms, 4.93 ms, 10° and 240 Hz/pixel, respectively. Generalised autocalibrating partially parallel acquisition with a parallel acquisition factor of 2 was utilised, producing a scanning time for this sequence of 8 min 30 s. This study was undertaken as a component of a larger MRI study that featured additional sequences, and the total scanning time for the entire scanning procedure was approximately 32 min.

Outcome Measures

Age, sex, height and weight were recorded for all participants. Body mass index (BMI) was calculated for all participants, and duration of symptoms was recorded for WAD group participants. WAD group participants were asked to describe the distribution of their neck pain (upper, middle, lower neck; left, right, middle, bilateral) and headache pain (front, middle, back; left, right, middle, bilateral). They were asked to rate the intensity of pain on average over a one-week period, for both neck pain and headache pain using an 11-point numerical pain scale (NPS) (Farrar et al., 2001). Participant NPS scores were categorised as ‘mild’ (NPS 0-3) or ‘moderate-severe’ (NPS 4-10) based on data reported by Sterling et al. (2003). Participants were asked to rate pain-related disability on a five-point Likert scale, using Item 8 of the Short Form 36 Health Survey: “*During the past 4 weeks, how much did pain interfere with your normal work (including both work outside the home and housework)? ...Not at all, a little bit, moderately, quite a bit, extremely*” pp482-483 (Ware & Sherbourne, 1992).

Images were reviewed and assessed by a medical scientist researcher (S.K.) in collaboration with a postdoctoral researcher (S.F.) with three years’ experience undertaking research on cervical spine meniscoid morphology using MRI, including training by a senior radiologist. OsiriX v3.0.2 imaging software (Pixmeo, Geneva,

Switzerland) was employed to review and measure the scans. Images were viewed in the sagittal plane on a Dell P2210 1.76 megapixel monitor (Dell Inc., Round Rock, TX), and researchers were blinded to the study group allocation of the scans during assessment.

Each LAA joint was inspected for the presence of meniscoids. The volume of each identified meniscoid was then determined by first manually tracing a cross-sectional area region of interest around each meniscoid (Figure 1) on all contiguous images on which the meniscoid was discernible, consistent with the technique described by Webb et al. (2009). For each meniscoid, all of the cross-sectional areas measures were summed, and then multiplied by the sequence slice thickness (0.6 mm) to calculate meniscoid volume in mm^3 . To account for normal variation in participant size, measures of meniscoid volume were also quantified as a percentage of articular cavity volume. Articular cavity volume was assessed using the same approach as meniscoid volume: cross-sectional area regions of interest were manually traced around the articular cavity in each contiguous sagittal plane image in which the cavity was visible. For the purpose of these measurements, the boundaries of the articular cavity were defined as the joint capsule at the ventral and dorsal aspects of the joint, and as the meeting of articular cartilage and subchondral bone at the superior and inferior aspects of the joint. The latter was used in the measurement of articular cavity volume to reduce variability and error in measurement, as the contrast between the dark subchondral bone and grey cartilage forms an easily discernible line that can be consistently identified and traced (Figure 1). These measures were summed, and then multiplied by the sequence slice thickness to calculate articular cavity volume in mm^3 .

Figure 1 Magnetic resonance image of sagittal section through lateral atlantoaxial joint demonstrating (a) ventral and dorsal meniscoids (VM and DM respectively) using T1-weighted volumetric interpolated breath-hold examination sequence with fat suppression. (b) Region of interest outlines of ventral meniscoid (orange) and dorsal meniscoid (blue) and articular cavity (red)

Intrarater reliability was tested on the scans of six randomly selected participants (approximately 20% of the sample), with one month separating first and second measurements. Reliability was tested for measurement of meniscoid volume in mm^3 and quantification of meniscoid volume as a percentage of articular cavity volume. Interrater reliability testing for these outcome measures was also undertaken on the same six randomly selected participants, comparing the measures of the medical scientist researcher (S.K.) with those of the experienced postdoctoral researcher (S.F.).

Data Analysis

Data were analysed using Stata 13.1 (StataCorp, College Station, TX) statistical analysis package. The distribution of continuous variables (i.e., meniscoid volume and BMI) was examined descriptively and using Shapiro-Wilk testing. Paired t-tests and Wilcoxon signed-rank testing was used to compare paired group data (i.e., meniscoid volume, BMI), as appropriate to distribution. Correlation between meniscoid volume and BMI was examined using Spearman Rho testing. Linear regression was used to explore the association between meniscoid volume and age, and meniscoid volume and WAD duration. Multiple logistic regression was used to explore meniscoid volume as a predictor of dichotomised severity of pain and disability. Two-way, absolute

agreement intra-class correlation coefficients (ICC [3,1]) were used to assess intra- and interrater reliability.

Significance was set at $\alpha < 0.05$.

Results

Participants

Fourteen people with Grade II WAD with pain in a possible LAA joint distribution (mean [SD] age 38.1 [10.8] years; six female) and 14 matched pain-free control participants (38.0 [10.5] years; six female) volunteered for the study. A resulting total of 56 LAA joints were assessed. Median (IQR) BMI for the WAD group was 24.1 kg/m² (22.5, 29.3), and for the control group was 25.0 kg/m² (23.0, 26.6). This difference was not significant ($z = 0.41$, $p = 0.68$).

WAD Participant Symptoms

In the WAD group, mean (SD) duration of symptoms was 13.4 (12.8) years. Mean (SD) NPS score was 4.7 (1.9). Participant NPS scores were categorised as ‘mild’ (NPS 0-3, $n = 5$) or ‘moderate-severe’ (NPS 4-10, $n = 9$). Location of participant symptoms and reported pain-related disability can be seen in Table 1. Pain-related disability responses were categorised as ‘mild’ (“*Not at all*” or “*A little bit*” Likert scale responses, $n = 6$) or ‘moderate-severe’ (“*Moderately*”, “*Quite a bit*” or “*Extremely*” Likert scale responses, $n = 8$).

Reported Symptom Details	n (%)
<i>Unilateral or central/bilateral symptoms?</i>	
Unilateral symptoms	7 (50)
Central or bilateral symptoms	7 (50)
<i>Location of symptoms in potential LAA joint distribution</i>	
Posterior cranial/suboccipital/upper cervical regions	9 (64.3)
Mid-cranial region	1 (7.1)
Anterior cranial region	2 (14.3)
Both anterior and posterior cranial/suboccipital/upper cervical regions	2 (14.3)
<i>Concurrent mid- or lower cervical spine symptoms?</i>	
Yes	7 (50)
No	7 (50)
<i>Pain-related disability (as per Item 8 of SF-36)</i>	
“Not at all”	3 (21.4)
“A little bit”	3 (21.4)
“Moderately”	4 (28.6)
“Quite a bit”	4 (28.6)
“Extremely”	0 (0)
Legend: LAA – lateral atlantoaxial. Item 8 of SF-36 (Short Form 36 Health Survey) is as follows: “During the past 4 weeks, how much did pain interfere with your normal work (including both work outside the home and housework)?” pp482-483 (Ware & Sherbourne, 1992)	

Table 1 Location of symptoms and reported pain-related disability for WAD group participants (n = 14)

Meniscoid Presence and Volume

Ventral and dorsal meniscoids were identified in both LAA joints of all WAD group and control group participants. No association was found between age and ventral LAA joint meniscoid volume as a percentage of articular cavity volume ($\beta = 0.02$, $p = 0.67$, adjusted $R^2 = -0.02$). A negative association was noted between age and dorsal LAA joint meniscoid volume as a percentage of articular cavity volume ($\beta = -0.12$, $p = 0.01$, adjusted $R^2 = 0.09$). No significant correlation was found between BMI and meniscoid volume in mm^3 (ventral:

Spearman rho = 0.20, p = 0.13; dorsal: Spearman rho = -0.09, p = 0.50). Meniscoid volumes for both the WAD and control groups, including results of corresponding paired t-tests, are presented in Table 2.

	WAD Group Mean (SD)	Control Group Mean (SD)	p
Ventral (mm ³)	131.9 (40.0)	133.2 (47.2)	0.90
Dorsal (mm ³)	131.6 (44.3)	147.3 (56.0)	0.29
Ventral (%)	15.7 (3.3)	14.9 (4.0)	0.39
Dorsal (%)	15.5 (3.1)	16.4 (4.2)	0.33
Legend: mm ³ – volume expressed in cubic millimetres; % - volume expressed as percentage of articular cavity volume; SD – standard deviation; WAD – whiplash associated disorder			

Table 2 Lateral atlantoaxial joint meniscoid volumes for WAD and control groups (n = 14 each group), with accompanying results of paired t-tests

Meniscoid Volume and WAD Symptoms

Symptom Duration

No association was found between duration of symptoms and ventral LAA joint meniscoid volume, when age was held constant, if meniscoids were quantified in cubic millimetres (symptom duration: $\beta = -1.13$, $p = 0.17$, adjusted $R^2 = 0.15$) or as a percentage of articular cavity volume (symptom duration: $\beta = 0.02$, $p = 0.79$, adjusted $R^2 = -0.05$). Similarly, no association was found between duration of symptoms and dorsal meniscoid volume, when age was held constant, if meniscoids were quantified in cubic millimetres (symptom duration: $\beta = -1.27$, $p = 0.20$, adjusted $R^2 = 0.02$) or as a percentage of articular cavity volume (symptom duration: $\beta = -0.01$, $p = 0.93$, adjusted $R^2 = -0.01$).

Symptomatic Side

For the seven participants with unilateral symptoms, LAA joint meniscoid volumes on the symptomatic side compared to corresponding joints in matched controls, including results of corresponding paired t-tests, can be seen in Table 3. Mean meniscoid volume was not significantly different between the WAD and control groups at the ventral or dorsal aspects of the joint, when measured in mm³ or as a percentage of articular cavity volume. Meniscoid volumes for the seven WAD participants with unilateral pain can be seen for both the symptomatic

and asymptomatic sides in Table 4. Mean meniscoid volumes were not significantly different for within participant comparisons of the symptomatic and asymptomatic sides (Table 4).

	WAD Group Mean (SD)	Control Group Mean (SD)	p
Ventral (mm ³)	124.0 (27.4)	157.3 (46.4)	0.13
Dorsal (mm ³)	120.6 (45.3)	164.9 (62.7)	0.20
Ventral (%)	15.5 (2.0)	15.6 (3.3)	0.96
Dorsal (%)	14.6 (3.0)	16.0 (4.4)	0.37
Legend: mm ³ – volume expressed in cubic millimetres; % - volume expressed as percentage of articular cavity volume; SD – standard deviation; WAD – whiplash associated disorder			

Table 3 Lateral atlantoaxial joint meniscoid volumes on the symptomatic sides of WAD group participants with unilateral pain (n = 7), compared to corresponding joints in matched controls, with accompanying results of paired t-tests

	Symptomatic Side	Asymptomatic Side	p
	Mean (SD)	Mean (SD)	
Ventral (mm ³)	124.0 (27.4)	130.1 (31.8)	0.29
Dorsal (mm ³)	120.6 (45.3)	132.5 (62.8)	0.44
Ventral (%)	15.5 (2.0)	15.3 (2.5)	0.67
Dorsal (%)	14.6 (3.0)	15.0 (4.2)	0.75
Legend: mm ³ – volume expressed in cubic millimetres; % - volume expressed as percentage of articular cavity volume; SD – standard deviation; WAD – whiplash associated disorder			

Table 4 Lateral atlantoaxial joint meniscoid volumes for WAD group participants with unilateral pain (n = 7) for symptomatic and asymptomatic sides, with accompanying results of paired t-tests

Dichotomised Pain and Disability

Dichotomised NPS (mild pain: 0-3 NPS; moderate-severe pain: 4-10 NPS) was modelled as an outcome with meniscoid volume and age as predictors in the WAD group. No significant association existed between LAA joint meniscoid volume in mm³ and moderate-severe pain at the ventral (OR = 1.01, p = 0.37, likelihood ratio test [LRT] chi-square₂ = 1.20, p = 0.55) or dorsal (OR = 1.01, p = 0.21; LRT chi-square₂ = 2.12, p = 0.35) aspects of joints.

No significant association was noted between LAA joint meniscoid volume as a percentage of articular cavity volume and moderate-severe pain at the ventral aspect of joints (OR = 1.07, p = 0.62; LRT chi-square₂ = 0.60, p = 0.74). A significant association was found however between meniscoid volume as a percentage of articular cavity volume and moderate-severe pain at the dorsal aspect of joints (OR = 1.48, p = 0.03; LRT chi-square₂ = 6.64, p = 0.04), indicating that meniscoids with larger proportional volume were more likely to occur in participants with moderate-severe pain.

Dichotomised disability was modelled as an outcome with meniscoid volume and age as predictors in the WAD group participants. No significant association existed between LAA joint meniscoid volume in mm³ and moderate-severe disability at the ventral (OR = 1.01, p = 0.21; LRT chi-square₂ = 1.85, p = 0.40) or dorsal (OR = 1.00, p = 0.72; LRT chi-square₂ = 0.22, p = 0.89) aspects of joints. No significant association was noted between meniscoid volume as a percentage of articular cavity volume and moderate-severe disability at the ventral (OR = 0.99, p = 0.93; LRT chi-square₂ = 0.1, p = 0.95) or dorsal (OR = 0.93, p = 0.55; LRT chi-square₂ = 0.46, p = 0.79) aspects of joints.

Intra- and Interrater Reliability

The intra- and interrater reliability test values can be seen in Table 5. For meniscoid volume expressed in mm³ as well as a percentage of articular cavity volume, ICCs were consistent with 'fair to good' reliability, as classified by Fleiss (1986).

Variable Measurement	ICC	95% CI
<i>Intrarater</i>		
Volume (mm ³)	0.80	0.60, 0.91
Volume (%)	0.79	0.58, 0.90
<i>Interrater</i>		
Volume (mm ³)	0.85	0.69, 0.93
Volume (%)	0.75	0.51, 0.88
Legend: mm ³ – volume expressed in cubic millimetres; % - volume expressed as percentage of articular cavity volume; CI – confidence interval; ICC - intra-class correlation coefficient		

Table 5 Intra-class correlation coefficients for intra- and interrater reliability of measures of lateral atlantoaxial joint meniscoid volume

Discussion

This novel exploratory study has examined LAA joint meniscoid volume in a living population with chronic WAD pain in possible LAA joint pain distributions and investigated this measure of morphology with respect to pain-related outcomes, as well as comparing meniscoid morphology with pain-free participants. While between group differences for ventral and dorsal meniscoid volumes for the WAD and control groups were not significantly different, an association was noted between severity of pain and meniscoid volume, indicating that dorsal meniscoids with larger volume, relative to articular cavity volume, were more likely to exist in patients with moderate-severe pain ratings. This is the first study to investigate the relationship between LAA joint meniscoid morphology and participant symptoms.

Farrell et al. (2016a) found LAA joint meniscoids to have smaller anterior-posterior protrusion lengths in people with chronic WAD as compared to pain-free controls, however their study did not examine meniscoid volume

and did not report data regarding participant symptoms. While it should be acknowledged that anterior-posterior protrusion length and volume are related but distinct outcome measures, the present study in contrast found there were no significant differences between meniscoid volumes of the WAD and control groups, nor between the symptomatic and asymptomatic sides in patients with unilateral WAD pain. This may be a consequence of the small sample size of the present study, or alternately suggests that LAA joint meniscoid anterior-posterior protrusion length differs between WAD and control individuals but meniscoid volume does not.

Clinical Considerations

The present study provides exploratory data inferring a possible association between LAA joint meniscoid morphology and symptoms in a chronic WAD population, in that proportionally larger dorsal meniscoids were associated with higher reported pain levels. When considered in the context of biomechanical evidence indicating LAA joints to be subject to forces exceeding physiologic limits during a whiplash injury (Grauer et al., 1997), as well as autopsy evidence of LAA joint meniscoid bruising in victims of fatal MVCs (Schonstrom et al., 1993; Taylor & Taylor, 1996), it is plausible that the differences observed may be linked with the pathoanatomy of a whiplash injury. It may be speculated that larger meniscoids could be more readily impacted between articular surfaces during a whiplash injury (Khan & Farrell, 2016). Further to this, dorsal LAA joint meniscoids have been noted to contain more plentiful vascular networks than ventral meniscoids (Schonstrom et al., 1993), and in post-mortem studies of victims of fatal MVCs, the dorsal meniscoids have been reported to demonstrate bruising more frequently than the ventral meniscoids in the LAA joint (Schonstrom et al., 1993; Taylor & Taylor, 1996) and in cervical zygapophyseal joints (Uhrenholt et al., 2009). Differences in innervation between ventral and dorsal components of LAA joint capsules have been described by Farrell et al. (2016b), with nerves being identified in joint capsules adjacent to dorsal meniscoids at twice the frequency to that of capsules adjacent to ventral meniscoids. These neurovascular characteristics of dorsal LAA joint meniscoids potentially make these structures susceptible to bruising and noxious sensory input if impacted between articular surfaces in whiplash trauma, and this may be reflected in the observed association of increased dorsal meniscoid size with higher levels of pain.

Conversely, the association of larger dorsal LAA joint meniscoids with higher levels of pain may suggest that these structures have increased in size since injury, in a similar manner to observed fibrous hypertrophy of synovial plicae in snapping elbow (Antuna & O'Driscoll, 2001; Kim et al., 2006). However, it should be noted

that the cross-sectional nature of the study design prevents inference of causation of the observed association, and as such these speculations should be approached with a degree of caution.

A precedent exists for a relationship between musculoskeletal morphology and clinical factors in chronic WAD, in the form of fatty infiltration of cervical spine muscles being associated with poor outcome (Elliott et al., 2011). Appreciation of potential changes in cervical spine morphology and their relationship with symptoms in chronic WAD may advance our understanding of mechanisms underpinning this condition. While the implications of the findings of the present study for clinical patient management are not yet clear, they may have future utility in diagnostics and development of novel approaches to treatment.

Limitations

While the distribution of pain for WAD group participants is consistent with established pain maps for LAA, it was not within the scope of this study to empirically confirm whether participants' pain arose from the LAA joints. As such, some participants' pain may have arisen from other structures, or may have been primarily centrally driven (i.e. not somatic in origin). Future research comparing cervical spine meniscoids to patient symptoms should employ diagnostic joint blocks (Cooper et al., 2007) to corroborate LAA or zygapophyseal joints as a source of nociceptive input in participants. This was an exploratory study using a subset of eligible participants from a larger morphological study (Farrell et al., 2016a), and consequently the sample size is modest, particularly for the analyses of WAD group individuals with unilateral pain.

Time since injury may influence theorised changes in meniscoid morphology following a whiplash injury, and as such it should be noted that the mean duration of symptoms for members of the WAD group was quite large at 13.4 years, with a considerable standard deviation of 12.8 years. Large variation in this parameter may have contributed to the non-significant findings of analyses, and future studies on this topic should consider this factor.

Conclusions

This novel exploratory study has identified an association between LAA joint meniscoid morphology and chronic WAD symptoms in a sample of individuals with pain in a potential LAA joint distribution. While no

significant between group differences existed, dorsal meniscoids with larger volumes, as a percentage of enclosing articular cavity volume, were associated with moderate-severe self-reported pain. These initial findings provide a platform for future investigations of LAA joint meniscoid volume in larger samples of symptomatic individuals, in order to advance understanding of the relationship between meniscoid morphology and WAD symptoms.

Ethical Statement: All procedures performed in this study were in accordance with the institutional research committees and with the 1964 Helsinki Declaration and its later amendments.

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Conflict of Interest: The authors declare that they have no conflict of interest.

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Appendix A

Figure Pain map approximating the distribution of pain arising from a lateral atlantoaxial joint – in the posterior upper cervical spine, sub-occipital region, and throughout the cranial region – as indicated by the findings of previous authors (Aprill et al., 2002; Cooper et al., 2007; Dreyfuss et al., 1994)