*J. Anat.* (2001) **198**, pp. 455–461, with 3 figures Printed in the United Kingdom

# An anatomical investigation of the human cervical facet capsule, quantifying muscle insertion area

BETH A. WINKELSTEIN[1], ROGER E. McLENDON[2], ANA BARBIR[3] AND BARRY S. MYERS[4]

[1] *Department of Biomedical Engineering*, [2] *Division of Orthopaedic Surgery*, [3] *Department of Pathology and* [4] *Department of Biological Anthropology and Anatomy*, *Duke University*, *Durham*, *N.C.*, *USA*

(*Accepted 7 November 2000*)

## ABSTRACT

Facet capsule injury has been hypothesised as a mechanism for neck pain. While qualitative studies have demonstrated the proximity of neck muscles to the cervical facet capsule, the magnitude of their forces remains unknown owing to a lack of quantitative muscle geometry. In this study, histological techniques were employed to quantify muscle insertions on the human cervical facet capsule. Computerised image analysis of slides stained with Masson's trichrome was performed to characterise the geometry of the cervical facet capsule and determine the total insertion area of muscle fibres into the facet capsule for the C4–C5 and C5–C6 joints. Muscle insertions were found to cover 22.4 ± 9.6 % of the capsule area for these cervical levels, corresponding to a mean muscle insertion area of 47.6 ± 21.8 mm$^2$. The magnitude of loading to the cervical facet capsule due to eccentric muscle contraction is estimated to be as high as 51 N. When taken in conjunction with the forces acting on the capsular ligament due to vertebral motions, these forces can be as high as 66 N. In that regard, these anatomical data provide quantitative evidence of substantial muscle insertions into the cervical facet capsular ligament and provide a possible mechanism for injury to this ligament and the facet joint as a whole.

*Key words*: Spine; facet joints; neck pain.

## INTRODUCTION

While the cervical facet capsule has been implicated as having a role in neck pain and whiplash injury (Barnsley et al. 1994; Lord et al. 1996; Panjabi et al. 1998), a broad range of hypotheses have been provided to suggest the mechanism of injury. Despite having received much attention through experimental studies regarding its injury (Yang & King, 1984; Yoganandan & Pintar, 1997, 1998; Winkelstein et al. 2000) and possible nervous tissue excitation (Cavanaugh et al. 1989, 1996; Avramov et al. 1992), the effects of muscle loading on the cervical facet capsule have not been well addressed in the literature. Anatomical investigations show that the semispinalis, multifidus, and rotator muscles are in close proximity to the cervical facet capsule (Kiefer & Heitzman, 1979; Agur, 1991; Lang, 1993). However, these observations do not quantify the extent of fibre insertion on the capsule. Recent studies have demonstrated paraspinal muscle activity in instrumented volunteer subjects of automobile collisions (Siegmund et al. 1997; Magnusson et al. 1999); this, together with the potential for muscle loading, suggests a possibility for capsular injury due to cervical muscle activation during some neck motions.

Muscle geometry has been used successfully to estimate muscle force. Unfortunately, quantitative data for muscle geometry in the cervical spine are limited. Historically, average geometric data on the cervical muscle cross-sectional areas have been reported (Berry, 1911; Eychleshymer & Schoemaker, 1911; Reber, 1978; Lieber, 1992; Kamibayashi & Richmond, 1998). While Kamibayashi & Richmond (1998) provided quantitative data on physiological cross-sectional area (PCSA) of neck muscles, this work did not quantify muscle insertions into the facet capsule. Relationships between muscle force and

Correspondence to Dr Barry S. Myers, Duke University, Department of Biomedical Engineering, Box 90281, Durham, NC, 27708-0281, USA. Tel. 001 (919) 660-5150; fax: 001 (919) 684-4488; e-mail: barry.myers@duke.edu

muscle geometry (either PCSA or true cross-sectional area) have also been reported for skeletal muscle (Lieber, 1992; Myers et al. 1998).

If the cervical musculature that is in close proximity to the facet capsule has insertions onto the facet capsule itself, direct loading of the joint capsule is possible when these muscles contract. However, to date no study has defined the anatomical relationship between the cervical musculature and the facet joint capsules. Therefore, estimates of muscle forces acting on the cervical facet capsule and the potential role of the cervical musculature in facet-mediated neck pain are unavailable. It is the purpose of this study to determine quantitatively the percentage of the cervical facet capsular ligament which is covered by musculotendinous insertions and to use these data to estimate muscle forces on the capsular ligament.

## MATERIALS AND METHODS

### *Specimen preparation*

Six human cervical spines and the surrounding musculature were removed from unembalmed cadavers from the C1 to the C7 level. The medical records and gross appearance of the donors were examined to exclude specimens with pathological conditions which would affect the integrity and anatomy of the specimens. Harvested spines were wrapped in cotton gauze, sprayed with saline solution, and frozen at −20 °C in a customised jig to preserve the neutral anatomical alignment for further dissection. Using the jig as a guide, a midsagittal osteotomy was performed dividing the spine into right and left sections. The right and left lateral masses, facet joints, and surrounding musculature from C4 to C6 were then isolated by axial osteotomies at the midbodies of C4 and C6. Parallel tissue sections for each of the C4–C5 and C5–C6 joint levels were prepared using a hand saw (blade thickness 0.635 mm). The superior-inferior height of each tissue section was measured before any chemical treatment. Sections were placed in 10% neutral buffered formalin (Stephens Scientific, Riverdale, NJ) for 3–5 d until adequately fixed.

### *Histological methods*

Each tissue section was processed for paraffin embedding using standard techniques and 15 pairs of slides were prepared from each section. Slide pairs (5 μm thick each slide) were cut sequentially at 150 μm intervals moving inferiorly from the superior surface of each tissue section. At each sample interval, one slide was stained using haematoxylin and eosin and a second slide was stained using Masson's trichrome stain. Each slide stained with Masson's trichrome was imaged using a CCD camera (Pulnix America, Sunnyvale, CA) having a 480 × 640 pixel matrix and a resolution of 42.5 μm per pixel.

### *Anatomical quantification*

An inverted microscope (Olympus Optical, Tokyo, Japan) was used at a magnification of ×10 to identify the facet capsule and muscle tissues for each of the Masson's trichrome slides. The length of the facet capsular ligament was digitised from the CCD images of each corresponding slide, using ImageTool software (UTHSCSA ImageTool, San Antonio, TX) (Fig. 1). Similarly, the length of each musculotendinous insertion into the capsule was also digitised (Fig. 1). Additional digitisation was performed around the perimeter of the cross-section of the facet capsule in the axial plane. A known length (4.4 mm) and areal (0.4 mm$^2$) calibration slide was digitised to provide conversion factors relating the digitised measurements in pixels to length and areal measurements in mm and mm$^2$. Separate calibration was performed for each set of slides taken from each tissue block.

Customised software was used to determine the length of the capsule and the total ligament cross-section from the digitised regions of the capsule in each slide. Similarly, the length of all muscle insertions was determined and summed to provide a total musculotendinous insertion length on the capsule length for each slide. The percentage of the capsule covered by the inserting musculature was determined for each slide. Axial cross-sectional area of the facet capsule was calculated by summing the number of pixels enclosed by the digitised ligament perimeter. Average geometric measurements (capsule ligament length, percentage muscle insertion, cross-sectional area) were derived for each specimen joint for all of the slides taken from each of the tissue sections comprising that joint. Total capsular ligament area was calculated by multiplying the average capsule ligament length for that joint by the total capsule height measured for the joint during preparation. Comparisons of muscle insertion area, capsule area, and axial cross-sectional area were made with cervical joint level, anatomical side (left vs right) and sex of donor. A Student's $t$ test was used to test for significance at a level of $P < 0.05$.

Additional analysis was performed to estimate the mechanical loading of the facet capsule due to muscle contraction. Muscle forces loading the capsular

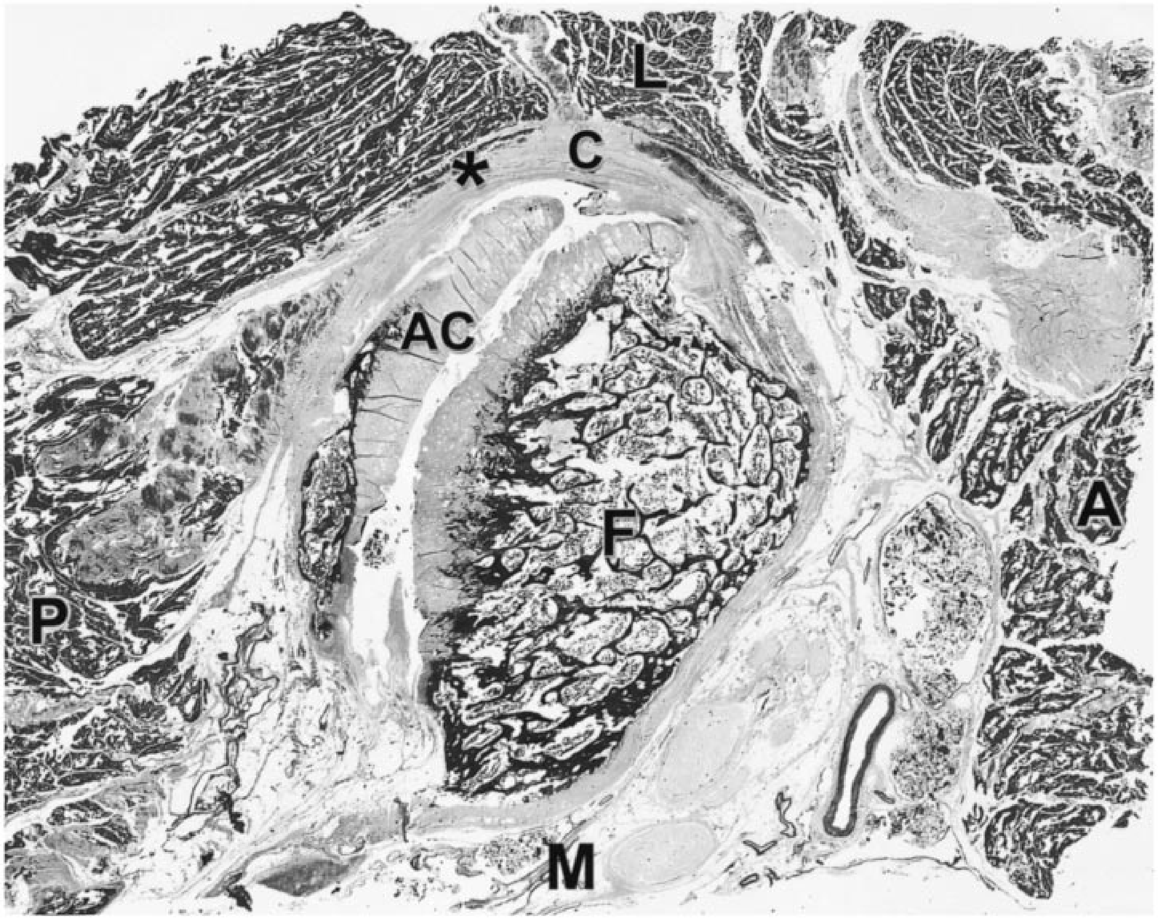

Fig. 1. Section indicating the left facet joint with its capsular ligament (C) surrounding the bony facets (F), articular cartilage (AC), and joint space of a typical C4–C5 articulation. The facet capsular ligament is visible along with the connecting muscles. Asterisk, one of the regions in this section where muscle fibres insert into the capsular ligament. Serial images were acquired spanning the superior-inferior height of this joint and the summation of the digitised insertion regions was used to determine the total muscle insertion area on the capsule. A, anterior; P, posterior; M, medial; L, lateral).

ligament and an estimate of the resulting capsular stress were derived from the determined muscular insertion and capsular ligament areas. Using engineering analysis, the force ($F_{\mathrm{musc}}$) generated during isometric muscle contraction can be estimated as the product of isometric muscle stress ($\sigma_{\mathrm{iso}}$) and the area ($A_{\mathrm{musc}}$) over which the muscle contraction force acts:

$$F_{\mathrm{musc}} = \sigma_{\mathrm{iso}} * \mathrm{A}_{\mathrm{musc}}. \tag{1}$$

In this case, the relevant area measurement is the muscle insertion area on the facet capsule as derived from the histological geometry measurements. To calculate this force estimation, an isometric stress of 0.44 MPa was used. This value has been reported as the isometric stress generated by mammalian skeletal muscle (Myers et al. 1998). Using a similar argument and engineering relationship, an estimate of the engineering tensile stress ($\sigma_{\mathrm{tensile}}$) in the facet capsule due to muscle loading across the joint's cross-section (i.e. along the joint's superior-inferior axis) was estimated for each specimen. In this calculation, the previously derived isometric muscle contraction force ($F_{\mathrm{musc}}$) is divided by the average axial capsular ligament cross-sectional area ($A_{\mathrm{cap}}$) for each specimen:

$$\frac{F_{\mathrm{musc}}}{A_{\mathrm{cap}}} = \sigma_{\mathrm{tensile}}. \tag{2}$$

Capsular ligament tensile stress was then compared between sexes for significant differences using a Student's $t$ test with significance at a level of $P < 0.05$.

## RESULTS

Twenty-one of the 24 cervical joints were available for analysis. These joints were taken from 3 female and 3 male cadavers (Table). The mean age of the 6 donors was 71.0 ± 6.0 y. In total, 10 C4–C5 joints and 11 C5–C6 joints were studied. Twelve of the joints came from the right side of the cervical spine and 9 from the left. In addition, 11 of the joints were taken from female donors while 10 came from male donors. Gross dissection of the cadaveric necks prior to sectioning

Table. *Summary of specimen geometric data*

| Joint ID | Age/sex | Capsule cross-section (mm$^2$) | Capsule height (mm) | Capsule boundary length (mm) | Capsule area (mm$^2$) | Muscle insertion area (mm$^2$) | Percentage muscle insertion |
|---|---|---|---|---|---|---|---|
| A45R* | 81/F | 10.4 | 14.3 | 14.7 | 210.6 | 36.0 | 17.1 |
| B45L | 72/F | 10.0 | 15.1 | 19.5 | 294.5 | 77.5 | 26.3 |
| B45R | 72/F | 8.9 | 9.9 | 16.0 | 158.2 | 8.9 | 5.6 |
| C45L | 67/F | 11.6 | 7.9 | 25.1 | 198.9 | 16.9 | 8.5 |
| C45R | 67/F | 11.8 | 8.7 | 19.1 | 166.9 | 27.0 | 16.2 |
| D45L | 67/M | 13.7 | 8.3 | 19.6 | 163.3 | 60.6 | 37.1 |
| D45R | 67/M | 14.8 | 10.3 | 20.8 | 214.7 | 55.2 | 25.7 |
| E45L | 65/M | 11.5 | 12.7 | 15.5 | 196.2 | 73.2 | 37.3 |
| E45R | 65/M | 16.8 | 9.5 | 19.1 | 182.1 | 75.0 | 41.2 |
| F45R | 74/M | 16.3 | 11.1 | 19.5 | 216.1 | 43.4 | 20.1 |
| A56L | 81/F | 7.8 | 7.9 | 19.9 | 158.2 | 41.1 | 26.0 |
| A56R | 81/F | 7.2 | 12.7 | 14.8 | 188.2 | 29.5 | 15.7 |
| B56L | 72/F | 12.1 | 10.7 | 29.3 | 314.5 | 40.9 | 13.0 |
| B56R | 72/F | 7.5 | 9.5 | 16.5 | 157.3 | 20.8 | 13.2 |
| C56L | 67/F | 10.0 | 10.7 | 20.9 | 223.8 | 32.2 | 14.4 |
| C56R | 67/F | 15.1 | 9.1 | 28.5 | 260.6 | 54.2 | 20.8 |
| D56L | 67/M | 14.6 | 13.5 | 19.3 | 259.8 | 60.3 | 23.2 |
| D56R | 67/M | 13.8 | 13.5 | 21.7 | 292.6 | 56.5 | 19.3 |
| E56L | 65/M | 22.7 | 11.9 | 27.2 | 323.4 | 96.0 | 29.7 |
| E56R | 65/M | 11.7 | 7.9 | 19.5 | 154.8 | 48.4 | 31.3 |
| F56R | 74/M | 10.8 | 9.5 | 17.0 | 161.5 | 45.2 | 28.0 |
| Mean** | 71.0 (6.0) | 12.3 (3.7) | 10.7 (2.2) | 20.2 (4.2) | 214.1 (55.6) | 47.6 (21.8) | 22.4 (9.6) |

* Specimen ID is comprised of donor label (A, B, C, D, E, F), cervical level (45 = C4–C5, 56 = C5–C6), and anatomical side (L = left, R = right).

** Data are given as mean (standard deviation).

revealed the close proximity of semispinalis and multifidus muscle fibres to the facet joints. However, given the nature of the technique used in this study to preserve the muscle insertions into the facet capsule, a detailed gross dissection following each muscle to document its insertions in the capsular ligament was not performed.

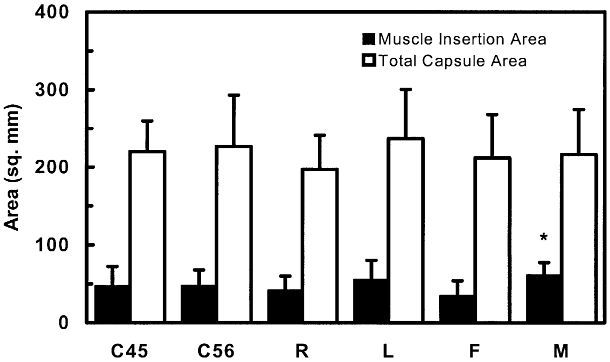

Fig. 2. Mean capsule and muscle insertion areas for the 21 specimens examined, according to cervical level (C45, C56), anatomical side (R, L), and sex of donor (F, M). Significant differences were observed only between males and females for muscle insertion area and the percentage of muscle covering the capsule. This significant difference is indicated by the asterisk in the graph.

The facet capsule was found to have muscular insertions over $22.4 \pm 9.6\%$ of its area. The mean percentage muscle area was significantly greater in male donors than in females ($P < 0.001$) (Fig. 2). Indeed, male donors had almost twice (1.82 times) the percentage muscle insertion area as did female donors. However, no significant difference was found when comparing the percentage of muscle coverage of the facet capsule between spinal levels ($P = 0.63$) or side of the body ($P = 0.53$) (Fig. 2). Total capsular ligament area was $214.1 \pm 55.6$ mm$^2$. No significant differences in this measurement were found between spinal levels ($P = 0.27$), anatomical side ($P = 0.13$), or sex ($P = 0.86$) (Fig. 2). The mean muscle insertion area onto the facet capsule was $47.6 \pm 21.8$ mm$^2$. Muscle insertion area did not vary significantly with cervical spinal level ($P = 0.97$) or anatomical side ($P = 0.18$) (Fig. 2). However, the mean muscle insertion area for males ($61.4 \pm 16.1$ mm$^2$) was significantly greater ($P < 0.003$) than the mean insertion area for female ($35.0 \pm 18.9$ mm$^2$). Interestingly, male donors had a body weight of $85.5 \pm 16.1$ kg and female donor body weight was $63.6 \pm 3.6$ kg. Thus the ratio of percentage muscle insertion area (1.75) for males versus females was greater than the ratio of their body masses (1.34). Mean facet capsule axial cross-sectional area was $12.3 \pm 3.5$ mm$^2$. This mea-

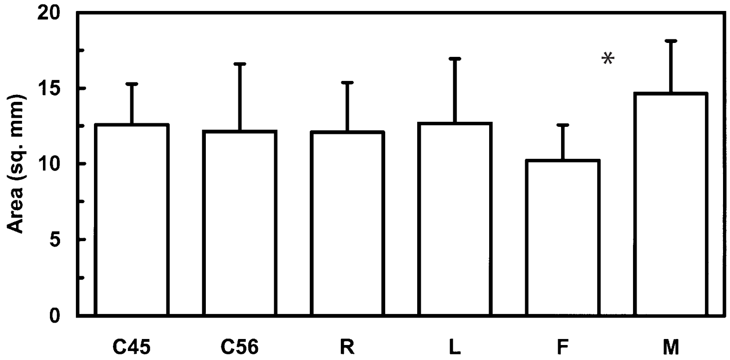

Fig. 3. Mean axial cross-sectional areas for the 21 specimens examined, according to cervical level (C45, C56), anatomical side (R, L), and sex of donor (F, M). Significant differences in the measured capsule areas were observed only between males and females and is indicated by the asterisk in the graph.

surement was significantly greater ($P < 0.002$) for males ($14.7 \pm 3.5\ \mathrm{mm}^2$) than females ($10.2 \pm 2.4\ \mathrm{mm}^2$) (Fig. 3).

Isometric muscle contraction was estimated to produce $20.9 \pm 9.6$ N of force on the capsular ligament. Loading due to muscular contraction was estimated as $27.0 \pm 7.1$ N for males and $15.4 \pm 8.3$ N for females. Further, the estimated mean tensile stress in the capsular ligament due to muscle forces was $1.9 \pm 0.4$ MPa for males and $1.5 \pm 0.8$ MPa for females. Thus, while muscle forces were significantly different between the sexes ($P = 0.0026$), the stresses were not significantly different ($P = 0.25$).

## DISCUSSION

The cervical facet capsule is a likely target for pain generation due to muscle contraction for a variety of reasons. Neurophysiological and neuroanatomical studies have documented neural receptors in the facet capsular ligament which have exhibited electrical activity in response to loading of this joint (Avramov et al. 1992; McLain, 1994; Pickar & McLain, 1995; Cavanaugh et al. 1996). The capsular ligament has the potential to be loaded by spinal motions (Yang & King, 1984; Yoganandan & Pintar, 1997, 1998; Winkelstein et al. 2000) and contraction of the surrounding cervical musculature (Szabo & Welcher, 1996; Siegmund et al. 1997; Kaneoka et al. 1999; Magnusson et al. 1999), either singly or by both mechanisms acting together. However, despite the possibility for capsule loading via muscle contraction and its potential injury, no study has addressed the effect of muscle loading to the capsular ligament. This work is the first to our knowledge to quantify muscle insertion area on the cervical facet capsule and provide quantitative anatomical data to further estimate the risk of injury to the facet capsule due to neck muscle loading.

While gross observations were made regarding the muscle groups in close proximity to the facet capsule, this study did not determine which specific muscles have fibres inserting onto the cervical facet capsule and there are currently no data on individual paraspinal muscle activation available in the literature. Therefore identification of the individual muscles from which these fibres arise would not provide a greater understanding of the muscle mediated capsular ligament forces.

The results of this investigation indicate that the human lower cervical facet capsule has an average of 22.4% of its area covered with muscle fibres, suggesting a potential path for loading of the facet capsule. Interestingly, no difference in insertion area was found based on cervical level. Thus, while supporting the possibility of muscle mediated facet capsular ligament injury, this result does not provide an anatomical basis for the clinical and epidemiological data which report that the C5–C6 level is the more common site of neck pain than the C4–C5 level (Bogduk & Marsland, 1988; Barnsley et al. 1995).

Forces acting on the facet capsule due to muscle contraction are large compared with the ligament's strength. A scaling factor of 1.5 has been used in the literature to estimate muscle force for stimulated muscle undergoing rapid elongation, as may occur during a whiplash injury, for example (Cole et al. 1996). Applying this scaling factor to muscle forces estimated in this study, loading of the facet capsule due to muscle contraction can be as high as 51.2 and 35.6 N for males and females, respectively. Partial ruptures of the facet capsule have been reported to occur at loads ranging from 48 to 121 N (Winkelstein et al. 1999). Muscle contraction forces represent an additional, parallel load path to the forces in the capsular ligament as a result of vertebral motions. Using data available in the literature, the force established in the cervical facet capsule for vertebral flexion and extension motions comparable to those observed during volunteer simulations of rear-end collisions is estimated to be as large as 14.4 N (Winkelstein et al. 1999). Superimposing the estimated muscle forces from this study on the derived capsular loads resulting from vertebral motions provides estimated forces of as high as 65.6 and 50.0 N for the cervical facet capsule for males and females, respectively. These magnitudes indeed fall within the range of forces at which partial rupture of the cervical facet capsule can occur. In that regard, the quantitative histology in this study suggests that loading due to contracting musculature, especially in conjunction with joint motion, may indeed be sufficient to cause partial rupture or injury of the cervical facet capsule. However, it should be noted that the muscle forces estimated in this study are based only on the available experimental data. Therefore, given that these estimates are not based on in vivo data, they may vary from the human response. While suggesting the importance of cervical muscles in neck pain, whiplash, and related neck motions, these data do not find a basis for the increased frequency of whiplash-related neck pain in women over men (Spitzer et al. 1995). Therefore, this sex difference is not due to muscle mediated facet capsular ligament forces and the basis for this difference must lie elsewhere, in another feature of the whiplash syndrome.

In conclusion, the cervical facet capsule geometry has been quantified using histological techniques. In addition, muscle insertions into the facet capsule have been quantified. Based on these data, loading to the cervical facet capsule by neck muscle contractions has been estimated and results indicate that the cervical facet capsule is indeed at risk for injury due to muscle contractions. This is the case, particularly when these contractions act in the presence of the forces which arise from vertebral motions stretching the facet capsule during whiplash and other such neck motions.

## ACKNOWLEDGEMENTS

This study was supported by the Department of Health and Human Services, Center for Disease Control Grant no. R49/CCR402396-12 and a National Science Foundation Fellowship. The authors gratefully acknowledge Ramona Nelson and Mary Jo Brown at the Duke Immunohistology Research Lab, Department of Pathology for histologic preparation.

## REFERENCES

AGUR AMI (1991) *Grant's Atlas of Anatomy*, p. 240. Baltimore, MD: Williams & Wilkins.

AVRAMOV AI, CAVANAUGH JM, OZATKAY AC, GETCHELL TV, KING AI (1992) Effects of controlled mechanical loading on group-II, III, and IV afferents from the lumbar facet joint: an in vitro study. *Journal of Bone and Joint Surgery* **74A**, 1464–1471.

BARNSLEY L, LORD S, BOGDUK N (1994) Whiplash injury. *Pain* **58**, 283–307.

BARNSLEY L, LORD SM, WALLIS BJ, BOGDUK N (1995) The prevalence of chronic cervical zygapophyseal joint pain after whiplash. *Spine* **20**, 20–26.

BERRY RJ (1911) *A Clinical Atlas of Sectional and Topographical Anatomy*. New York: William Wood.

BOGDUK N, MARSLAND A (1988) The cervical zygapophyseal joints as a source of neck pain. *Spine* **13**, 610–617.

CAVANAUGH JM, EL-BOHY AA, HARDY WH, GETCHELL TV, GETCHELL ML, KING AI (1989) Sensory innervation of soft tissues of the lumbar spine in the rat. *Journal of Orthopaedic Research* **7**, 378–388.

CAVANAUGH JM, OZAKTAY AC, YAMASHITA HT, KING AI (1996) Lumbar facet pain: biomechanics, neuroanatomy and neurophysiology. *Journal of Biomechanics* **29**, 1117–1129.

COLE GK, VAN DEN BOGERT AJ, HERZOG W, GERRITSEN KGM (1996) Modelling of force production in skeletal muscle undergoing stretch. *Journal of Biomechanics* **29**, 1091–1104.

EYCHLESHYMER AC, SCHOEMAKER DM (1911) *A Cross-Section Anatomy*. New York: Appleton-Century Crofts.

KAMIBAYASHI LK, RICHMOND JR (1998) Morphometry of human neck muscles. *Spine* **23**, 1314–1323.

KANEOKA K, ONO K, INAMI S, HAYASHI K (1999) Motion analysis of cervical vertebrae during whiplash loading. *Spine* **24**, 763–770.

KIEFER SA, HEITZMAN ER (1979) *An Atlas of Cross-Sectional Anatomy*, pp. 61–65. Hagerstown, MD: Harper & Row.

LANG J (1993) *Clinical Anatomy of the Cervical Spine*. New York: Thieme Medical.

LIEBER RL (1992) *Skeletal Muscle Structure and Function, Implications for Rehabilitation and Sports Medicine*. Baltimore, MD: Williams & Wilkins.

LORD SM, BARNSLEY L, WALLIS BJ, BOGDUK N (1996) Chronic cervical zygapophysial joint pain after whiplash. A placebo-controlled prevalence study. *Spine* **21**, 1737–1744.

MAGNUSSON ML, POPE MH, HASSELQUIST L, BOLTE KM, ROSS M, GOEL VK et al. (1999) Cervical electromyographic activity during low-speed rear impact. *European Spine Journal* **8**, 118–125.

McLAIN RF (1994) Mechanoreceptor endings in human cervical facet joints. *Spine* **19**, 495–501.

MYERS BS, WOOLLEY CT, SLOTTER TL, GARRETT WE, BEST TM (1998) The influence of strain rate on the passive and stimulated engineering stress-large strain behavior of the rabbit tibialis anterior muscle. *Journal of Biomechanical Engineering* **120**, 126–132.

PANJABI MM, CHOLEWICKI J, NIBU K, GRAUER J, VAHLDIEK M (1998) Capsular ligament stretches during in vitro whiplash simulations. *Journal of Spinal Disorders* **11**, 227–232.

PICKAR JG, McLAIN RF (1995) Responses of mechanosensitive afferents to manipulation of the lumbar facet in the cat. *Spine* **20**, 2379–2385.

REBER JG (1978) Lumped parameter model of whiplash. MS Thesis, University of California, Berkeley.

SIEGMUND GP, KING DJ, LAWRENCE JM, WHEELER JB, BRAULT JR, SMITH TA (1997) Head–neck kinematic response of human subjects in low-speed rear-end collisions. *Proceedings of the 41st Stapp Car Crash Conference*. Warrendale, PA: Society of Automotive Engineers, Inc., SAE Paper no. 973341, 357–385.

SPITZER WO, SKOVRON ML, SALMI LR, CASSIDY JD, DURANCEAU J, SUISSA S et al. (1995) Scientific monograph of the Quebec Task Force on whiplash-associated disorders: redefining 'whiplash' and it management. *Spine* **20**, 1S–73S.

SZABO TJ, WELCHER JB (1996) Human subject kinematics and electromyographic activity during low speed rear impacts. *Proceedings of the 40th Stapp Car Crash Conference*. Warrendale, PA: Society of Automotive Engineers, SAE Paper no. 962432, 295–315.

WINKELSTEIN BA, NIGHTINGALE RW, RICHARDSON WJ, MYERS BS (1999) Cervical facet joint mechanics: its application to whiplash injury. *Proceedings of the 43th Stapp Car Crash Conference*. Warrendale, PA: Society of Automotive Engineers, SAE Paper no. 99SC15, 243–252.

WINKELSTEIN BA, NIGHTINGALE RW, RICHARDSON WJ, MYERS BS (2000) The cervical facet capsule and its role in whiplash injury: a biomechanical investigation. *Spine* **25**, 1238–1246.

YANG KH, KING AI (1984) Mechanism of facet load transmission as a hypothesis for low-back pain. *Spine* **9**, 557–565.

YOGANANDAN N, PINTAR FA (1997) Facet joint local component kinetics in whiplash trauma. *Advances in Bioengineering* **36**, 221–222. New York: American Society of Mechanical Engineers.

YOGANANDAN N, PINTAR FA (1998) Biomechanical assessment of whiplash. In *Frontiers in Head and Neck Trauma* (ed. Yoganandan N, Pintar FA, Larson SJ, Sances A), pp. 344–373. Netherlands: IOS Press.