Localized cervical facet joint kinematics under physiological and whiplash loading

BRIAN D. STEMPER, PH.D., NARAYAN YOGANANDAN, PH.D., THOMAS A. GENNARELLI, M.D., AND FRANK A. PINTAR, PH.D.

Department of Neurosurgery, Medical College of Wisconsin; and Department of Veterans Affairs Medical Center, Milwaukee, Wisconsin

Object. Although facet joints have been implicated in the whiplash injury mechanism, no investigators have determined the degree to which joint motions in whiplash are nonphysiological. The purpose of this investigation was to quantify the correlation between facet joint and segmental motions under physiological and whiplash loading.

Methods. Human cadaveric cervical spine specimens were exercise tested under physiological extension loading, and intact human head-neck complexes were exercise tested under whiplash loading to correlate the localized component motions of the C4–5 facet joint with segmental extension. Facet joint shear and distraction kinematics demonstrated a linear correlation with segmental extension under both loading modes. Facet joints responded differently to whiplash and physiological loading, with significantly increased kinematics for the same-segmental angulation. The limitations of this study include removal of superficial musculature and the limited sample size for physiological testing.

Conclusions. The presence of increased facet joint motions indicated that synovial joint soft-tissue components (that is, synovial membrane and capsular ligament) sustain increased distortion that may subject these tissues to a greater likelihood of injury. This finding is supported by clinical investigations in which lower cervical facet joint injury resulted in similar pain patterns due to the most commonly reported whiplash symptoms.

KEY WORDS • impact injury • biomechanical testing • facet joint • physiological study • cadaveric dissection

C HRONIC and acute whiplash-related disorders are a significant societal problem with estimated associated annual costs of $4.5 billion.42 Most commonly reported initial symptoms include posterior neck pain and suboccipital headache.9,18,25,38 In the US and Canada there are between 70 and 380 claims for every 100,000 inhabitants.9,34,35 In the United Kingdom, it is estimated that whiplash disorders are responsible for 18% of costs attributed to all road traffic accidents.11 The exact injury mechanism and affected cervical structure(s), however, remain unknown. Hyperextension was originally cited as the mechanism of injury, subjecting anterior spinal structures to excess distortion.21 The addition of head restraints to all passenger vehicles in 1969 to minimize hyperextension, however, was not found to significantly reduce whiplash-related injuries.15,27

It has been proposed that eccentric muscle contraction during retraction (initial) and rebound phases is an injury mechanism involving the anterior and posterior neck muscles, respectively.5,20 Although this mechanism may account for acute complications, long-term persistence is unlikely because muscle injuries typically heal within a matter of weeks.3 Spinal canal pressure gradients due to relative translation of the head and thorax during the retraction phase may injure nerve roots.2 This mechanism is the basis for the neck injury criteria.7,39 Nerve root injury, however, is not likely responsible for the most common whiplash symptoms.3

Injuries involving lower cervical facet joints have more recently been hypothesized to occur in whiplash injury.4,10,31,36 Clinical evidence has supported this theory in one study in which nerve blocks of cervical facet joints relieved posterior neck pain and headache in whiplash-injured patients.4 In addition, investigators studying experimental intact head–neck complexes, isolated cervical spines, and cadavers have quantified localized facet joint kinematics during whiplash injury.2,10,20,31,36 Whiplash loading subjected these joints to uniform shearing motion across the sagittal plane while distraction in anterior and compression in posterior joint regions occurred during initial stages.36 This motion resulted in increased joint capsule tension in the anterior region, with greatest magnitudes observed at the C4–5 joint. The levels of tissue distortion, however, have only been hypothesized to be injurious because physiological controls do not exist. In addition, a complicating factor for the aforementioned facet joint injury theory is that segmental angulations

Abbreviations used in this paper: PMMA = polymethylmethacrylate; RDM = rate of distraction motion; RSM = rate of shear motion; VB = vertebral body.
(demonstrating the overall state of segmental soft-tissue distortion) in whiplash do not exceed normal physiological ranges of motion. Therefore, to validate the facet joint injury mechanism, it remains necessary to prove that facet joint motions in whiplash are different and increased compared with those sustained in normal physiological motion.

In the present study we hypothesized that a correlation exists between segmental angulations and facet joint motions under physiological and whiplash loading conditions and that this correlation is fundamentally different between these modes. In particular, whiplash loading subjects the lower cervical facet joints to increased distortion that may exceed local tissue thresholds and cause subcatastrophic or catastrophic injury. To test these hypotheses, facet joint kinematics and segmental angulations were analyzed during physiological and whiplash loading. In a previous study we demonstrated that maximal facet joint motions occurred at the C4–5 level. Perforce, in the present analysis we focus on this level.

Materials and Methods

Physiological Loading

The present protocol was approved for the use of human cadavers by our institution’s review board. Four unembalmed human ligamentous cervical spines free of preexisting trauma or significant degenerative disease were harvested from C-2 to T-2. The mean age of the patients (at death) in whom specimens were obtained was 60.5 years. Skin and superficial neck musculature were removed, leaving intact biomechanically relevant soft-tissue spinal components such as deep musculature, ligaments, and intervertebral discs. Each specimen was fixed in PMMA at its superior (C-2) and inferior (T-1) ends to facilitate mounting on the loading apparatus. The T-1 VB was orientated 25° anteriorly to facilitate normal lordotic spinal curvature. Photoreflective targets (3 mm diameter) were placed in the anterior VB and the lateral mass of C-4 and C-5. Smaller (1.5-mm-diameter) targets were placed at the four sagittal-plane corners of the C4–5 facet joint (Fig. 1).

The inferior end of the specimen was attached to the load frame through a six-axis load cell, and a cervical arch was attached to the superior edge of the C-2 PMMA fixative. The purpose of the arch was to transform pure superior–inferior loads, applied using the piston of a vertically oriented electrohydrodynamic testing device (MTS Systems Corp., Eden Prairie, MN), into physiological extension combined with compression. This loading approximated the weight of the head as the cervical spine was extended. Each specimen was quasistatically exercise tested at four loading magnitudes between 0.9 and 3.6 Nm, measured at the inferior load cell. Loading magnitudes were within the normal physiological limit for cervical spinal segments. Sagittal-plane target motions were digitally recorded at 250 Hz by using a high-resolution imaging system (Redlake MASD, Inc., San Diego, CA).

Whiplash Loading

Eight intact head–neck complexes, consisting of head, cervical spine, T-1 and T-2 vertebrae, and all biomechanically relevant soft tissues, were used for whiplash testing. The inferior end of the specimens was fixed in PMMA at T-1, which was given an anterior orientation of 25° to facilitate normal lordotic spinal curvature. Skin and neck musculature were attached to the PMMA base to approximate passive neck-muscle resistance. A small 5-cm-wide incision was made along the right lateral side of the neck to expose the cervical column. Photoreflective targets were placed on the C-4 and C-5 vertebrae in a manner identical to that used for physiological testing (for instance, larger targets in the VB and lateral mass, and four smaller targets to outline the facet joint).

The loading apparatus consisted of a pendulum and minisled on linear rails (Fig. 1 right). The specimen base was rigidly mounted to the minisled. Loading was applied by striking the posterior edge with the pendulum. After impact, sagittal-plane target motions were digitally recorded at 1000 Hz. The anterior minisled acceleration approximated the anterior acceleration of the thorax in a typical whiplash event and was measured using a uniaxial accelerometer. The anterior acceleration versus time trace was integrated to compute change in the velocity of the specimen base (T-1), a measure commonly used to quantify impact severity in the automotive literature. Each specimen was exposed to a 2.6-m/second rear impact, which is consistent with the range of velocities at which a majority of neck distortion injuries occur in rear impact events.

Data Reduction

Photoreflective targets were used to quantify segmental and facet joint motions at C4–5 under both loading modes. Temporal positions of larger targets were used to compute the C-4 relative to C-5 segmental angle. Smaller targets were used to quantify facet joint motions in a joint-specific localized coordinate system (Fig. 2). Shear (x-axis) and distraction (z-axis) motions were computed in the posterior and anterior joint regions as motion of superior relative to inferior targets. A positive shear motion was directed anteriorly. Distraction was defined as an increase in the z-axis distance between targets, whereas compression was defined as a decrease in that distance.

Temporal plots for segmental angulation and facet joint component motions (shear/distraction in anterior/posterior joint regions) were obtained. The time variable was eliminated to develop facet joint component motion compared with segmental extension. The data for the physiological tests were limited to the positive loading portion of the cycle (0 Nm to maximum loading). Whiplash-related data were limited to the time period from initiation of anterior acceleration to time of maximal cervical S-curve. A slope of these plots was computed to describe the rate of facet joint component motion as a function of segmental extension, referred to as the RSM or RDM.

Statistical Analysis

The slope of facet joint motion compared with segmental extension was determined using linear regression analysis, with β, equal to zero. The linearity of the correlation between these motions was assessed using the R2 statistic. Single-factor analysis of variance was used to determine statistically significant differences (p < 0.05) in RSM and RDM between physiological and whiplash tests.

Results

Sixteen physiological tests were performed, of which data obtained in 14 were analyzed for comparison to whiplash loading. Eight whiplash tests were performed. The mean maximal extensions C4–5 were 2.6 ± 1.5° in the physiological tests and 9.5 ± 3.8° in the whiplash tests. Strong linear correlations were obtained for RSM under physiological (R2 = 0.82) and whiplash (R2 = 0.80) loading (differences not statistically significant). Linear correlations for RDM in the anterior joint region for physiological (R2 = 0.40) and whiplash (R2 = 0.49) loading were weaker than correlations for RSM. The R2 values between the two loading modes, however, were not significantly different (p > 0.60). Linear correlation for RDM in the posterior joint region demonstrated statistically significant differences, with very low correlation for whiplash loading.

The correlation between segmental and facet joint motions for physiological and whiplash loading is illustrated in Fig. 3. For identical magnitudes of segmental extension, whiplash, in contrast to physiological loading, resulted in markedly increased facet joint motion. Under
segmental extension, the C4–5 anterior and posterior facet joint regions sustained approximately uniform posteriorly directed shear motion. The RSM magnitudes were significantly greater during whiplash than physiological loading in anterior (p = 0.0109) and posterior (p = 0.0303) joint regions (Fig. 4 left). The facet joints exhibited distraction in anterior joint regions during segmental extension. In the anterior region RDM was significantly greater for whiplash than physiological loading (p = 0.0203). Facet joints demonstrated mean compression in the posterior joint region during segmental extension. In the posterior joint region, however, RDM was not significantly different during physiological or whiplash loading, although physiological joint motions were generally greater (Fig. 4 right).

**Discussion**

In the present investigation we correlated facet joint shear and distraction motion with segmental extension under physiological and whiplash conditions. Analysis of the results demonstrated a strong linear correlation between facet joint RSM and segmental extension under both loading modes. Facet joint RDM exhibited a weaker linear correlation to segmental extension. As demonstrated in Fig. 3, identical magnitudes of segmental extension resulted in significantly increased RSM under whiplash than physiological loading conditions. In addition, whiplash loading resulted in significantly increased RDM for identical segmental extension magnitudes. Increased facet joint motions, particularly in the anterior joint regions, led to greater joint capsule distortion. Because these structures fail primarily in tension, present results indicate increased vulnerability of these structures to injury during whiplash. This injury can manifest as either subcatastrophic (joint strain) or catastrophic (ligament tear) pathological entities. To our knowledge, this is the first study in which the increased susceptibility of lower cervical facet joints in whiplash compared with physiological loading has been determined quantitatively.

**Phases of Whiplash Kinematics**

In this study we focused on the initial phase of head–neck kinematics during a whiplash (retraction) event. During this phase, relative motion between the head and thorax is similar to “chin-in” motion previously described by Penning. To compensate for this relative motion, the cervical spine transitions into a nonphysiological S-shaped curvature, with extension at lower (C4–5 and below) and flexion at upper (C2–3) spinal levels. Various injury mechanisms have been hypothesized to occur during this abnormal loading situation including distraction in anterior joint regions (in the present and other studies), compression in posterior joint regions, cervical nerve root damage due to spinal canal pressure gradients, and anterior neck muscle injury due to eccentric contraction. After the retraction phase, the head–neck complex transitions into extension and subsequently rebounds from the head restraint. It is generally hypothesized, however, that these phases are associated with a lower risk of injury. Our present focus on initial head–neck kinematics is justified because of the increased whiplash-induced facet joint motions (RSM and RDM) documented in this study.

**Correlation of Facet Joint Motion to Segmental Extension**

Analysis of our results indicated that the movement of the lower cervical facet joints is fundamentally different during whiplash than in normal physiological extension. This finding is illustrated schematically in Fig. 3, in which identical magnitudes of segmental angulation resulted in significantly increased facet joint motions. This finding

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**Fig. 1.** Schematic illustrations of the physiological (left) and whiplash (right) loading apparatus. Detailed segmental and facet joint target placement is demonstrated for whiplash loading.
explains why the facet joint exhibits increased vulnerability to injury during whiplash. The authors of previous investigations of whiplash-related cervical biomechanics focused primarily on absolute segmental angulations and facet joint kinematics. In the present study our focus on normalizing facet joint motions to segmental angulation permitted direct comparison of facet joint motions under both loading modes. This comparison revealed that facet joint motions are significantly increased in whiplash, resulting in greater joint capsule distortion and an increased susceptibility to injury.

Spinal Level Dependence

In the present study we quantified the correlation between facet joint and segmental kinematics at the C4–5 level. In our previous research we observed maximal facet joint motions at that level, although segmental angulations were maximal at inferior spinal levels. The facet joint study also demonstrated minimal motions in the upper cervical spine. This finding underscores the importance of measuring localized component motions in the development of whiplash injury hypotheses. Localized kinematics detail specific soft-tissue distortions such as joint capsule strain in anterior joint regions. Correlating segmental and localized motions under physiological and whiplash conditions aids in our understanding of normal spinal kinematics and the method by which whiplash fundamentally alters spinal biomechanics.

Facet Joint Injury and Nociception

Recently investigators have identified nerve fibers and neuropeptides essential to nociception in facet joint components. Components of the synovial joint receiving some form of innervation include capsular ligaments, synovial membranes, and subchondral bone. Therefore, increased soft-tissue distortion may lead to a nociceptive response. The initiation and persistence of pain are often mediated by pain-sensitive neuropeptides, such as Substance P and calcitonin gene–related peptide. These neu-
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ropeptides may have longlasting hyperalgesic effects. Soft-tissue injury may elicit ingrowth of neuropeptide-positive nerve fibers. Recently, immunocytochemical analysis identified these substances in human cervical facet joints. The present findings of whiplash-induced increased facet joint motions, coupled with previous observations of nociception with increased joint excursion, implicate lower cervical facet joints in acute or chronic whiplash disorder. The persistence of facet joint pain after whiplash, as reported in a clinical series, supports this conclusion.

Limitations of the Study

One limitation of this study was that superficial musculature was removed from the specimens subjected to physiological loading, whereas whiplash specimens remained intact. The kinematic effect of this procedure was hypothesized to be minimal because the deep musculature with spinal attachment was left primarily intact. The clinical stability of the cervical spine in bending is primarily modulated by intervertebral ligaments, with muscles having only a secondary effect. Therefore, the removal of superficial musculature likely had a minimal effect on the correlation between facet joint and segmental motions in physiological extension.

A second limitation was that only half as many specimens were used for physiological testing as for whiplash loading. Whereas eight specimens were subjected to the whiplash protocol, only four specimens were tested under physiological loading; however, the sample size was sufficient to identify statistically significant differences in an analysis of variance with a mean power of 68% for RSM in anterior and posterior joint regions and 67% for RDM in the anterior joint region. Therefore, the limited number of specimens subjected to physiological loading was sufficient to support the conclusion that facet joint motions are significantly increased during whiplash loading.

Conclusions

An experimental model was used to quantify the degree to which dynamic whiplash loading alters the correlation of localized facet joint kinematics and segmental extensions from normal physiological motions. Analysis of the results demonstrated a strong linear correlation for facet joint shear motion relative to segmental extension, with a decreased correlation for facet joint distraction motion. Whiplash loading fundamentally altered spinal biomechanics by significantly increasing the rate of facet joint motion in segmental extension, resulting in a greater joint capsule distortion that may lead to localized tissue failure and nociception. Clinical findings of facet joint–induced pain after whiplash, coupled with the present findings of significantly increased facet joint motions during whiplash, implicate the lower cervical facet joints in the whiplash injury mechanism. To our knowledge, this is the first study to demonstrate that facet joints respond differently in whiplash than under normal physiological extension conditions, which may be the reason for the increased injury susceptibility of the joint capsule during whiplash.

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Address reprint requests to: Brian D. Stemper, Ph.D., Department of Neurosurgery, Medical College of Wisconsin, 5000 West National Avenue, Research 151, Milwaukee, Wisconsin 53295. email: stempe@mcw.edu.