

Stabilizing Effect of Precontracted Neck Musculature in Whiplash

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Study Design. This study investigated the effect of neck muscle precontraction in aware occupants in whiplash. Head angulation relative to T1 and facet joint capsular ligament distractions were compared between aware and unaware occupants.

Objective. To quantify changes in facet joint capsular ligament distractions between aware occupants with precontracted neck muscles and unaware occupants with reflex muscle contraction.

Summary of Background Data. Clinical studies have reported that patients aware of the impending impact had decreased symptom intensity and faster recovery after whiplash. To date, no study has investigated the effects of precontracted neck musculature on localized spinal soft tissue distortions in whiplash.

Methods. Aware occupants with precontracted neck muscles and unaware occupants with reflex muscle contraction in whiplash were simulated using a validated computational model. Muscle contraction attained maximum levels before impact in the aware occupant and implemented reflex delay, electromechanical delay, and finite muscle rise time in the unaware occupant.

Results. Precontraction of neck muscles in aware occupants resulted in 63% decreased maximum head angles, elimination of cervical S-curvature, and up to 75% decrease in maximum facet joint capsular ligament distractions.

Conclusions. Occupants aware of an impending whiplash impact with precontracted neck muscles can markedly reduce overall head-neck and spinal motions. It is our theory that this would reduce whiplash injury likelihood.

Key words: whiplash, biomechanics, neck muscles, facet joints, cervical spine. **Spine 2006;31:E733–E738**

resulting in abnormal differential motions between the head and thorax. These differential motions are distributed among the segments of the cervical spine and initially result in an abnormal S-shaped spinal curvature with flexion at upper and extension at lower levels (Figure 1). This abnormal spinal curvature was previously shown to result in nonphysiologic facet joint motions.⁴ In response to the event, neck muscles are contracted and result in stiffening of the head-neck complex to reduce relative head-neck motions, which also reduces spinal motions. Muscle contraction may occur reflexively after initiation of thoracic acceleration in the completely unaware occupant or before thoracic acceleration in the occupant aware of the impending impact.

Clinical studies have identified a possible role of awareness in whiplash outcome. In a study of 137 referred whiplash patients, awareness of the impending impact resulted in significantly lower frequency of multiple symptoms and intensity of headache pain.⁵ Results of a randomized clinical study enrolling 125 whiplash patients supported the previous findings in that unpreparedness was associated with poor recovery 12 weeks after injury.⁶ These studies highlighted the ability of the aware occupant to reduce the likelihood of injury by taking some preventative action before impact (e.g., contracting neck muscles). Another study indicated that reflexive tension of the neck or shoulder muscles may be a protective mechanism in whiplash.⁷ Biomechanical investigations of neck muscle ability to alter spinal mechanics during whiplash have not been conclusive.

The effect of reflex neck muscle contraction in unaware occupants has been investigated using human volunteers and computational modeling. Correlating EMG with head-neck kinematics, volunteer studies demonstrated that reflex contraction occurs before the time of maximum head-neck motion, which typically occurs later in the event (88–171 ms).^{8–10} Based on the relative timing of these events, it was theorized that reflex contraction can reduce the likelihood of injury by stiffening the head-neck complex and limiting maximum motions. However, a recent computational modeling study demonstrated that reflex neck muscle contraction in the unaware occupant has a minimal effect on spinal kinematics during initial whiplash stages due to inherent delays in the contraction mechanism.¹¹ In particular, reflex contraction decreased cervical spinal segmental kinematics by a maximum of only 19% during the retraction phase. It has been theorized that injury occurs during this initial stage, before the time of maximum head-neck motions,

Whiplash injuries continue to have a considerable effect on society.^{1–3} These injuries commonly result from automotive rear impact, wherein the struck vehicle is accelerated forward. This, in turn, accelerates the occupant's thorax anteriorly due to interaction with the seatback,

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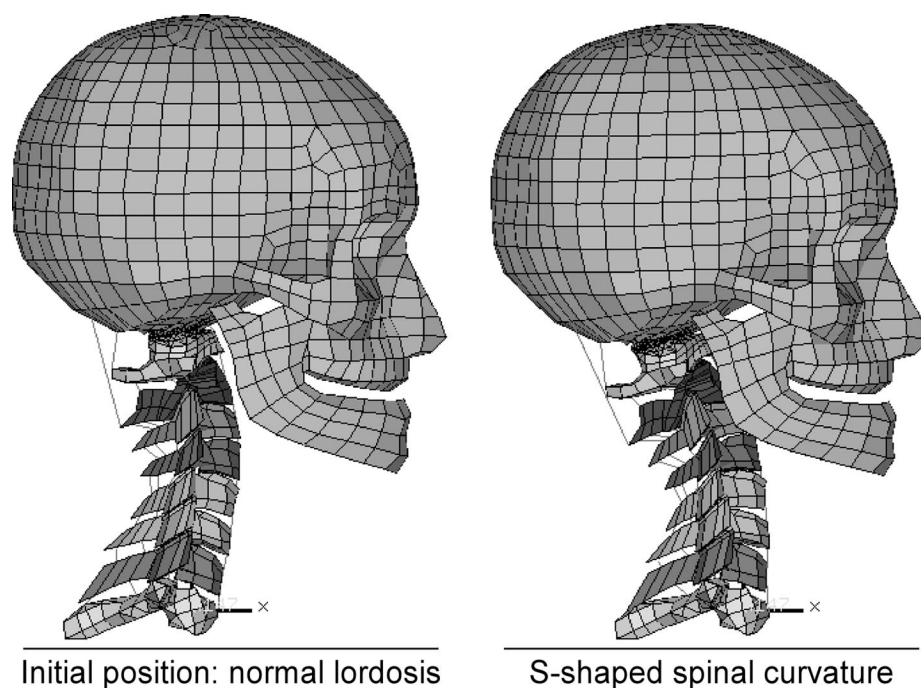


Figure 1. Computational model illustration of normal lordotic curvature and S-shaped cervical curvature resulting from retraction of the head relative to T1.

due to abnormal S-shaped cervical curvature and non-physiologic lower cervical facet joint motions.^{4,12–16} The ability of reflex contraction to reduce spinal motions is limited by inherent delays in the development of maximum contraction levels. Contraction delays include “reflex delay” characterized as the time between the stimulus and initiation of electrical muscle activity, “electromechanical delay” characterized as the time between initiation of electrical muscle activity and mechanical force generation, and “muscle force rise time” characterized as the steady rise in muscle force magnitude to the maximum contraction level.¹⁷ As maximum S-curvature occurs at approximately 76 ms for 9-km/hr rear impacts,¹⁶ neck muscles may not be capable of reflexively responding in time to generate sufficient forces to alter spinal kinematics and decrease whiplash injury likelihood.

Experimental human volunteer studies have investigated the effect of precontracted neck muscles on whiplash biomechanics in aware occupants.^{18–21} While these studies typically identified kinematic changes in volunteers made aware of the impending whiplash acceleration, kinematic results were primarily limited to overall motions of the head and thorax. However, whiplash injuries affect cervical spinal structures, such as facet joints.^{4,12,22–26} To our knowledge, no study has investigated the effect of precontracted neck muscles on cervical soft tissue distortions (*e.g.*, facet joint capsular ligaments) during whiplash. The purpose of this investigation was to quantify changes in facet joint capsular ligament distractions between aware occupants with precontracted neck muscles and unaware occupants with reflex muscle contraction initiating postimpact. Based on previous clinical and experimental findings, it was expected that precontraction of neck muscles would reduce

the level of soft tissue distortion during initial whiplash stages, which would correlate with a decreased likelihood of injury in aware occupants.

Materials and Methods

A computational model was used to investigate the effect of awareness on spinal kinematics in whiplash.^{27–29} The model was exercised using MADYMO computer modeling software (TNO Automotive, Delft, The Netherlands) and consisted of the head, seven cervical vertebrae (C1–C7), first thoracic vertebra (T1), and all relevant soft tissues of the spine. Bony geometry was obtained from CT scans. Passive soft tissue material properties were obtained from literature and included ligament tension,^{30,31} intervertebral axial, shear, and bending,^{32–34} facet joint compression,³⁵ and muscle tension.³⁶ Extensive kinematic validation against *in vitro* and *in vivo* experimental data, consisting of overall head-neck motions,^{19,37} vertebral and segmental angulations,^{12,16,19} and localized ligament distractions,³⁸ ensured realistic response of the model to whiplash acceleration.

Sixteen neck muscle pairs were included, consisting of flexors, extensors, and sternocleidomastoids. Contraction characteristics including physiologic cross-sectional area, maximum stress (70 N/cm²), relative shortening velocity (6/s), and muscle length were obtained from literature.^{35,39–42} Maximum contraction levels were adjusted to obtain a sagittally balanced contraction scheme, wherein equal flexion and extension bending moments were applied to the head-neck complex. Aware occupant simulations attained maximum contraction levels before initiation of whiplash acceleration (Figure 2). Unaware occupant simulations implemented minimal muscle activation to balance the head before initiation of acceleration. Reflex contraction was initiated after acceleration of T1 and consisted of a 50-ms reflex delay, 13-ms electromechanical delay, and an 81-ms muscle rise time.¹¹

Aware and unaware occupant simulations were subjected to 10.5-km/hr rear impacts. Before impact, the model was ori-

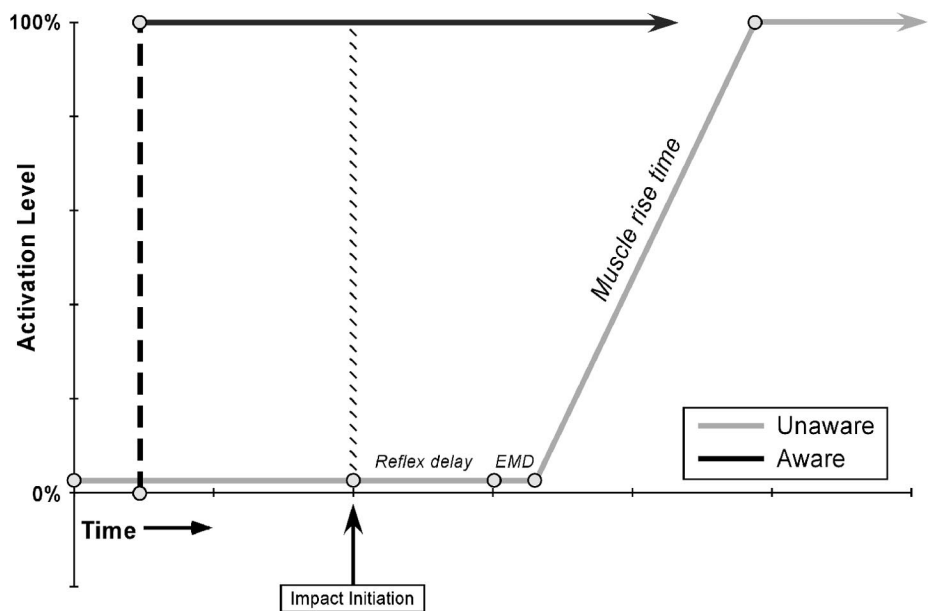


Figure 2. Timing of neck muscle contraction in aware and unaware occupants.

ented with lordotic spinal curvature according to literature,⁴³ Frankfort plane horizontal, and occipital condyles positioned directly superior to the T1 vertebral body. The input pulse was applied as an anterior acceleration of T1, which was constrained against rotation and lateral and vertical displacement. Sagittal plane angle of the head relative to T1 was compared between aware and unaware occupant simulations. Maximum facet joint capsular ligament distractions were obtained in ventral, dorsal, medial, and lateral joint regions at levels C4–C5 through C6–C7. Maximum facet joint ligament distractions were compared between aware and unaware simulations.

Results

Secondary to whiplash acceleration, the unaware occupant computational model demonstrated retraction, extension, and rebound kinematic phases. These kinematic phases were characterized by cervical spinal S-shaped

curvature, overall extension of the head and neck, and rebound of the head due to neck muscle contraction, respectively. Although retraction of the head relative to T1 was evident in the aware occupant, S-shaped spinal curvature did not occur as upper cervical segments extended immediately following whiplash acceleration. Following retraction, the aware occupant transitioned into head-neck extension followed by rebound of the head toward the initial orientation. Maximum extension angulation of the head relative to T1 was considerably reduced in the aware occupant (Figure 3). Maximum head extension decreased from 82.7° in the unaware occupant with reflex contraction to 30.5° in the aware occupant with precontracted neck muscles.

Lower cervical (C4–C7) facet joint capsular ligament distractions were greatest in the lateral joint region for

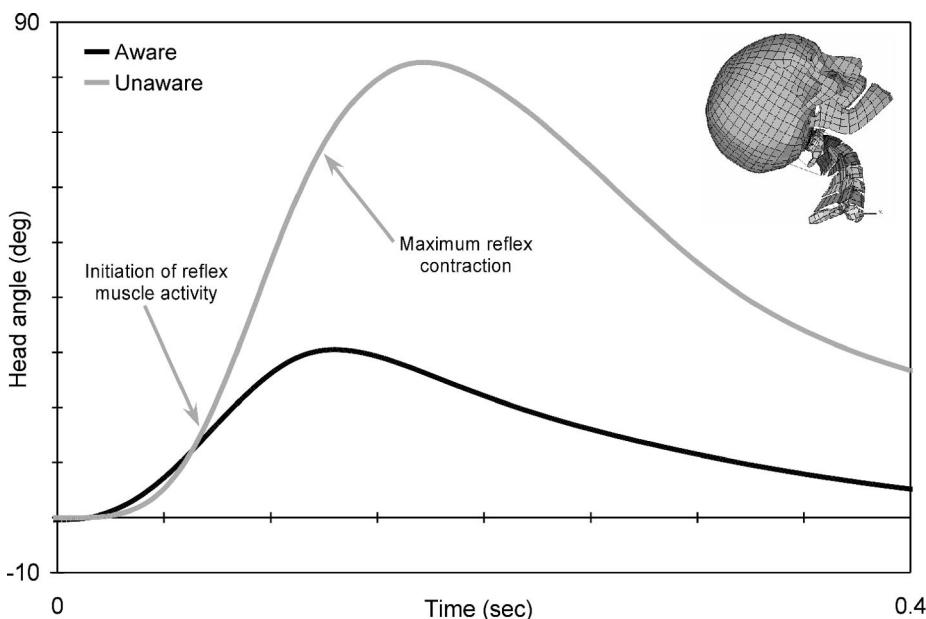


Figure 3. Temporal sagittal plane head extension relative to T1. Extension rotation is positive. Timing landmarks for reflex contraction are indicated.

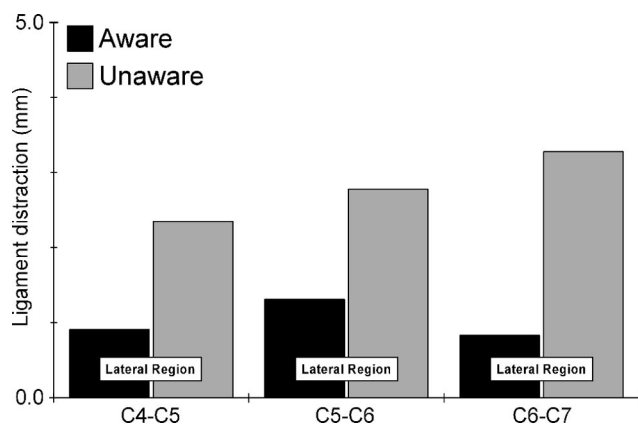


Figure 4. Maximum lower cervical facet joint capsular ligament distractions in aware and unaware occupants.

both simulations. Precontraction of neck muscles considerably and consistently decreased maximum capsular ligament distraction magnitudes at C4–C5 through C6–C7 spinal levels by an average of 63% (Figure 4). The greatest decrease in ligament distraction occurred at C6–C7, wherein maximum distraction magnitudes were decreased by 75%. Maximum ligament distractions occurred between 22 and 41 ms earlier in the aware occupant.

Discussion

A head-neck computational model was used to investigate the effect of occupant awareness on localized spinal kinematics in whiplash. The model was comprehensively validated against human volunteer, human cadaver, head-neck complex, and isolated cervical column whiplash experimentation. Computational modeling was ideal for this application. Experimentation using human volunteers suffers from limitations such as the inability to measure localized spinal kinematics, subinjury input acceleration levels, and an inherent level of habituation that may bias unaware simulations.⁴⁴ Human cadavers, while sufficient to study injury mechanisms in whiplash, cannot replicate the neck muscle tone necessary for this application. The present model permitted detailed analysis of localized spinal kinematics and soft tissue distortions with strict control of neck muscle contraction levels and timing.

The present model was subjected to 10.5-km/hr rear impacts. These rear impacts exceeded the level previously cited as “unlikely to result in significant injury.”⁴⁵ It is generally thought that increasing impact severity leads to a greater likelihood of injury. However, this does not explain passengers in very high-velocity rear impacts who remain uninjured.⁴⁶ A possible explanation for this finding is that a number of occupant- and crash-related factors influence whiplash injury likelihood and outcome. It was previously demonstrated in clinical studies that gender,^{47–51} age,^{46,48} cervical posture,^{52,53} head restraint backset,^{5,54} head position,⁵ and awareness of the impending impact, among others, affected whiplash in-

jury. Biomechanical studies have, to some degree, supported these clinical findings. For example, experimental human volunteer¹⁰ and cadaver^{16,26} investigations reported increased head and cervical spine motions during the retraction phase in females. The model implemented in this study was also used to demonstrate effects of head restraint positioning⁵⁵ and abnormal spinal posture⁵⁶ on cervical spine biomechanics. Therefore, from a biomechanical standpoint, impact severity is an important factor in determining patient outcomes after automotive rear impacts. However, it cannot be applied as an exclusive factor in determining whether an occupant will be injured or the extent of injury in a specific rear impact collision.

Present results demonstrated the ability of precontracted neck musculature to stabilize the head-neck complex during whiplash and reduce spinal motions and soft tissue distortions. Our hypothesis is that decreased tissue distortion, particularly for facet joint capsular ligaments, correlates with a decreased likelihood of injury, nociception, and allodynia. Because of the presence of nociceptors and pain-facilitating neuropeptides in facet joints, increased distortion leading to partial or complete tear of the joint capsule may result in the perception of pain.^{57–60} Although the present model was incapable of identifying joint capsule failure or reproducing the perception of pain, recent findings demonstrated increased rates of allodynia in rats subjected to facet joint distraction.⁶¹ The ability of an aware occupant to decrease facet joint distractions by up to 75% will markedly reduce the possibility of injury under identical levels of whiplash loading.

Although head restraints were introduced into passenger vehicles to reduce the likelihood of whiplash injury, these devices have had a limited effect on patient outcomes after automotive rear impacts.^{62–64} A possible explanation for limited head restraint effectiveness is that the head-neck complex sustains nonphysiologic kinematics (retraction leading to S-shaped cervical curvature) before head restraint contact unless the head restraint is oriented in an optimum position.⁵⁵ Field studies have demonstrated that adjustable head restraints are often not positioned correctly to protect the head-neck complex during whiplash.^{65–67} Therefore, neck muscle contraction is a primary means of occupant protection in rear impact. Present results demonstrated that timing of neck muscle contraction is critical to reducing spinal soft tissue distortions that may lead to whiplash injuries. Aware occupants with precontracted neck muscles demonstrated markedly reduced head-neck motions and facet joint capsular ligament distractions along with elimination of cervical S-curvature under identical levels of rear impact loading. In contrast, unaware occupants did not initiate muscle contraction until after the start of thoracic acceleration. Because of inherent delays in the mechanism of contraction, head-neck motions attained 14% of maximum levels before the initiation of neck muscle contraction and 93% of maximum levels by the

time neck muscles attained maximum contraction. This delay resulted in considerably increased soft tissue distortions in the facet joints and a corresponding increase in whiplash injury likelihood for the unaware occupant.

Present results of decreased head-neck motions in aware occupants are supported by previous human volunteer whiplash experimentation. Volunteers exposed to 6-km/hr rear impacts without head restraints and with pretensed neck musculature demonstrated 30% to 40% decreased maximum head extension compared with relaxed volunteers subjected to identical impacts.⁶⁸ Another study reported increased head-neck motions in surprised (unaware) human volunteers compared with gender-matched unalerted but aware and alerted volunteers.²⁰ Similarly, Mertz and Patrick²¹ hypothesized that precontracted neck musculature will reduce the likelihood of whiplash injury due to decreased neck torques in volunteers with pretensed muscles compared with cadavers subjected to identical impacts. Results of the present study demonstrated a 60% decrease in maximum head extension in the aware occupant. This decrease in head-neck motion resulted in a decrease in total angulation of the cervical spine, distributed nonuniformly among cervical segments. Cervical segmental motions directly resulted in distortion of soft tissues such as facet joint capsular ligaments and intervertebral discs.

Facet joint capsular ligament distractions were measured in ventral, lateral, dorsal, and medial joint regions at levels C4–C5 through C6–C7 for aware and unaware occupant simulations. Ligament distractions were greatest in the lateral joint region at each level for both simulations. Because of anterior-to-posteriorly directed shear motion experienced by lower cervical facet joints during the whiplash retraction phase,⁴ it may be expected that fibers located ventrally and dorsally would sustain maximum distraction magnitudes. However, because of fiber directions and relative orientations of caudal and cranial lateral masses, the lateral region sustained greatest distortion magnitudes during initial whiplash stages. Lateral fibers, oriented perpendicular to the direction of joint motion, were distracted immediately on initiation of anterior-to-posterior shear motion. Ventrally and dorsally located fibers sustained initial laxity, due to the vertical orientation of fibers and cervical facet joint angles of approximately 45° in the sagittal plane. Therefore, anterior-posterior facet joint shear resulted in posteriorly and inferiorly directed motion of the superior process. Initial motion during the retraction phase, therefore, brought ligament insertion points closer together and resulted in initial joint capsule laxity. From a physiologic standpoint, the present findings of increased stretch in the lateral joint region underscore the importance of quantifying distributions of capsular ligament distraction magnitudes across the plane of the joint capsule^{22,23} as it pertains to nerve fiber innervation of the joint.

■ Conclusion

The present study demonstrated that occupants aware of the impending impact with precontracted neck muscles can markedly reduce overall head-neck and spinal motions. In particular, facet joint capsular ligament distractions were decreased by up to 75% in the aware occupant. Because of the role of facet joints in the perception and persistence of whiplash pain, it is our theory that decreased ligament distractions in lower cervical joints will lead to markedly reduced whiplash injury likelihood.

■ Key Points

- Aware occupants attained maximum muscle contraction levels before impact while reflex neck muscle contraction in unaware occupants did not initiate until after impact and implemented reflex delay, electromechanical delay, and finite muscle rise time.
- Precontraction of neck muscles in aware occupants eliminated cervical S-curvature, decreased maximum head-neck extension magnitude by 63%, and decreased maximum facet joint ligament distractions between 53% and 75%.
- Because of decreased soft tissue distortion, it is our theory that whiplash injury likelihood is markedly decreased in occupants aware of the impending impact.

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