A Computational Model for Assessing Potential Strain Injury to the Musculotendonous Junction of Rectus Capitis Posterior Minor Muscles as a Function of Head Restraint Backset Prior to a Rear-End Motor Vehicle Accident

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The manuscript submitted does not contain information about medical device(s)/drug(s).

No benefits in any form have been or will be received from a commercial related directly or indirectly to the subject of this manuscript.

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Abstract

Background: Whiplash injuries, resulting from rear-end motor vehicle accidents (REMVAs), are caused by excessive loading and displacement of structural components of the cervical spine. Some whiplash injury patients with chronic head and neck pain show a statistically significant increase in fatty infiltration (FI) of rectus capitis posterior minor (RCPMi) muscles on MRI. While the cause of FI in RCPMi muscles is currently unknown, forced lengthening of these muscles could result in strain injuries similar to those known to occur at the musculotendonous junction of knee and shoulder muscles which are characterized by FI of the injured muscles.

Objective: The goal of this project was to develop a computational model that would estimate risk of strain injury to RCPMi muscles by predicting the magnitude of strain within these muscles as a function of head restraint backset prior to impact. The possibility that a REMVA might generate forces of sufficient magnitude to produce a strain injury sufficient to result in FI of RCPMi muscles has not been previously studied.

Methods: A computational model of the OA joint, based upon geometric, morphologic and kinematic data obtained from peer-reviewed scientific journals, was developed. This model was used to estimate forced changes in OA joint angle as a function of head displacement during the retraction phase of a REMVA. Changes in RCPMi muscle length, calculated as a function of OA joint angle, were then used to calculate strain within the RCPMi muscles.

Results: Values of RCPMi muscle strain were found to exceed previously reported injury thresholds for skeletal muscle. For a given value of backset while driving, having an increase in the component of backset that was due to protrusion of the head resulted in a disproportionate increase in muscle strain when compared to the same increase in backset due to adjustment of the head restraint in a stationary vehicle.

Conclusions: Protrusion of the head while driving puts drivers at greater risk for experiencing higher levels of strain in RCPMi muscles during a REMVA. This is the first time that a computational model has predicted injury to a structural component of the upper cervical spine that would account for pathology that is detectable on standard clinical diagnostic MRI and seen in some whiplash patients suffering from chronic head and neck pain. This knowledge has the potential to guide diagnostic and treatment strategies that would lessen the rate of transition for some individuals from an acute to a chronic condition.

Key Words: Whiplash, Injury mechanism, Computational model, Head restraint, Upper cervical spine.

Introduction

A rear-end motor vehicle accident (REMVA) has the potential to cause head and neck injuries resulting in both acute and chronic symptoms (Siegmund et al. 2009) that are often difficult to treat because of the absence of specific and consistent anatomic and physiologic pathologies. While recent studies have focused upon kinematics and risk of injury to structures of the lower cervical spine during a REMVA (Ivancic 2011), little has been published that addresses the kinematics and risk of injury to structures of the upper cervical spine.

Fatty infiltration (FI) of suboccipital muscles has been reported in patients suffering from whiplash-type injuries (Hallgren et al. 1994; Andary et al. 1998). Studies demonstrate significant amounts of FI on MRI in spinal segments of patients suffering from persistent whiplash-associated disorders (WAD) at and above C3, with the rectus capitis posterior major (RCPMa) and minor (RCPMi) muscles having significantly larger amounts of fatty infiltrate (Elliott et al. 2006). The cause of FI in RCPMi muscles is currently unknown, and it is unlikely that FI is the direct cause of the long-term pain (Bogduk 2005). FI has not been observed in cervical extensor muscles in females (mean age 29.2±6.9 years) with persistent insidious-onset neck pain (Elliott et al. 2005). FI of suboccipital muscles is unrelated to age in healthy females between the ages of 18-45 years who have not had a whiplash type injury (Elliott et al. 2008).

RCPMi muscles arise from the posterior tubercle of the posterior arch of C1 and insert into the occipital bone inferior to the inferior nuchal line and lateral to the midline. RCPMi muscles are the only muscles that attach to the posterior arch of C1. Their fascicles run at a slightly superolateral angle of 5-40 degrees measured relative to the midline (Kamibayashi and Richmond 1998; Borst et al. 2011). Forces associated with a REMVA result in forced flexion of the occipitoatlantal (OA) joint along with forced stretching of RCPMi muscles (Grauer et al. 1997). When a muscle is forcibly stretched, strain in the muscle, defined as the ratio of the change in length of the muscle divided by the initial length of the muscle and expressed as a percentage, can result in a strain injury to the muscle. RCPMI muscles cross one vertebral segment and would be expected to have a higher risk of injury for a given level of strain than muscles that cross two or more segments, such as the cervical multifidus (Brooks and Faulkner 2001; Anderson et al. 2005). Normally, injured muscles repair themselves in a few days (Nikolaou et al. 1987). However, sudden and forceful lengthening of a muscle can result in strain injuries to the musculotendonous junction that do not readily resolve (Gerber et al. 2007). Strain injury is characterized on MRI by edema and inflammation in the early stages, followed by FI of the muscle. FI is directly related to the severity of the tear and the longer that the condition is allowed to continue. The goal of surgical intervention is be to repair the tear, minimizing FI and functional loss (Melis et al. 2009).

The musculotendonous junction is the weakest link in normal, healthy muscles and is a common site of injury in forced-extension injuries (Garrett et al. 1988; Sun et al. 1998). Mechanical testing of tibialis anterior muscles from New Zealand white rabbits produced failure at the musculotendonous junction at axial strain rates of 40 cm/s (Best et al. 1995). Structural failure has been reported to occur in the belly of the muscle, but only at axial strain rates of 310 cm/s (Lin et al. 1999). When a tendon is torn, the muscle shortens and, if the tear is not surgically repaired, irreversible FI, along with the loss of normal functionality, occurs (Gerber et al. 2009). However, if the tear is repaired within 6 weeks of the injury, the progression of FI can be halted and muscle function can be retained (Rubino et al. 2008).

Head and neck kinematics resulting from a REMVA can be characterized by retraction and rebound phases (Vasavada et al. 2007). During the first 100 ms of the retraction phase, the inertia of the driver's head causes it to translate posteriorly, without rotation, relative to thoracic vertebra T1. This results in an 'S'-shaped curvature in the cervical spine that is characterized by flexion at the OA joint and extension at lower levels (Cholewicki et al. 1998; Grauer et al. 1997; Vasavada et al. 2007) that results in high levels of strain in suboccipital muscles (Hedenstierna et al. 2009). Flexion of the OA joint continues to increase until the head restrain contacts the driver's head. Active head restraints have been designed to limit differential movement of the head and torso by actively moving the head restraint closer to the driver's head during a REMVA (Ivancic et al. 2009). Backset is defined as the horizontal distance between the head restraint and the posterior aspect of the driver's head. Values of backset, measured when the driver is engaged in normal driving activities, have been shown to be significantly larger than values of backset measured when the vehicle is stationary (Jonsson et al. 2008). Once the vehicle is moving, backset has been found to remain constant except when performing right turns (Shugg et al. 2011).

Flexion of the OA joint during the retraction phase of a REMVA is very similar to flexion of the OA joint during voluntary retraction of the head (See Figure 1). Forces that drive the thoracic spine forward and upward during a REMVA result in sudden flexion of the OA joint along with forced lengthening of the RCPMi muscles. Forces that produce voluntary retraction of the head also result in flexion of the OA joint along with lengthening of the RCPMi muscles. Both result in a characteristic 'S'-shaped curve as a result of flexion, primarily at the OA joint, and extension at lower cervical levels. During voluntary retraction, the head moves in a posterior direction without rotation. During the retraction phase of a REMVA, the head also moves in a posterior direction without rotation. One significant difference between the two mechanisms of flexion is that forces producing flexion of the OA joint during a REMVA are applied in a relatively short period of time.

Figure 1. Flexion of the OA joint as a result of voluntary retraction of the head.

The goal of this project was to develop a computational model that would estimate risk of strain injury to the musculotendonous junction of RCPMi muscles by predicting the magnitude of muscle strain expressed as a function of head restraint backset measured just prior to a REMVA. A computational model can complement experimental studies that have used human subjects and cadavers by estimating strain in tissues as a function of selected boundary conditions that would otherwise not be possible. This model fills an important gap in our knowledge and understanding of a whiplash injury mechanism specifically related to the upper cervical spine by providing insight into whiplash injury mechanisms that cause FI of RCPMi muscles. The possibility that a REMVA might generate forces of sufficient magnitude and within a sufficiently short period of time to produce a strain injury sufficient to result in FI of RCPMi muscles has not been previously studied.

Materials and Methods

Model Assumptions

The model is assumed to be valid from the time of impact to the time when the head restraint contacts the driver's head. The head restraint is assumed to have an angled front surface (See Figure 2a) that is incompressible. Therefore, for a driver in a self–selected neutral position with the vehicle stationary, vertical adjustment of the head restraint will also change backset.

Previous studies have used thoracic vertebra T1 as a reference point to describe motion of the head and neck (Cholewicki et al. 1998; Panjabi et al. 2005; Stemper et al. 2006; Vasavada et al. 2007). Our model, driven by head kinematics relative to T1, does not rely on geometry or mechanical properties of physiologic structures located between T1 and the head in order to estimate rotation of C1 relative to C0 (Vasavada et al. 2007). C0 is assumed to translate with respect to T1 within a sagittal plane with negligible rotation. C1 is assumed to translate along with C0 while rotating within a sagittal plane about C0. RCPMi muscles were modeled as straight lines from their proximal attachment point on C0 to their distal attachment point on C1 (Anderson et al. 2005).

Cervical multifidus muscles contract in response to the impact of a simulated REMVA (Siegmund et al. 2008). Subjects who are aware of the impending impact show markedly reduced head/neck motions along with reduction of the S-shaped curvature (Stemper et al. 2006). It has been proposed that muscle activation could reduce distraction of the articular joints and reduce strain in cervical ligaments (Fice et al. 2011). Our model assumes that the driver is unaware of the impending impact and that reflex contraction of cervical muscles does not occur in sufficient time to significantly alter spinal kinematics (Stemper et al. 2005).

Independent Variables

We defined the origin of a local reference axis system at the most posterior aspect of the head when the driver has positioned their head in a self-selected, neutral position (NHP). Measurements in an anterior direction are considered to be positive; measurements in a posterior direction are considered to be negative.

Three independent variables were defined:

- Static Backset (SB): SB (See Figure 2a) defines the magnitude of the distance measured from the most posterior aspect of the driver's head to the head restraint with the vehicle stationary and the driver positioned so that their head is in a self-selected, neutral position (NHP). Values of SB varied from 0 to -8 cm. SB is equal to 0 when the head restraint is adjusted so that it touches the most posterior aspect of the driver's head.

- Forward Head Position (FHP): Typically, drivers do not maintain a NHP while driving (Jonsson et al. 2008). FHP defines the driver's head position relative to the NHP while the driver is engaged in normal driving activities. Values of FHP varied from 4.8 to -2.4 cm. Positive values represent protrusion of the head relative to the NHP; negative values represent retraction of the head relative to the NHP.
- Dynamic Backset (DB): DB (See Figure 2b) defines the magnitude of the distance measured from the most posterior aspect of the driver's head to the head restraint, when the driver is engaged in normal driving activities. DB is equal to the maximum amount of posterior head translation that would occur in a REMVA given the backset measured in a stationary vehicle (SB) and the magnitude of protrusion/retraction (FHP) of the driver's head just prior to impact (DB = FHP - SB).

Independent Variables

Two dependent variables were calculated:

- OA joint angle.
- RCPMi strain.

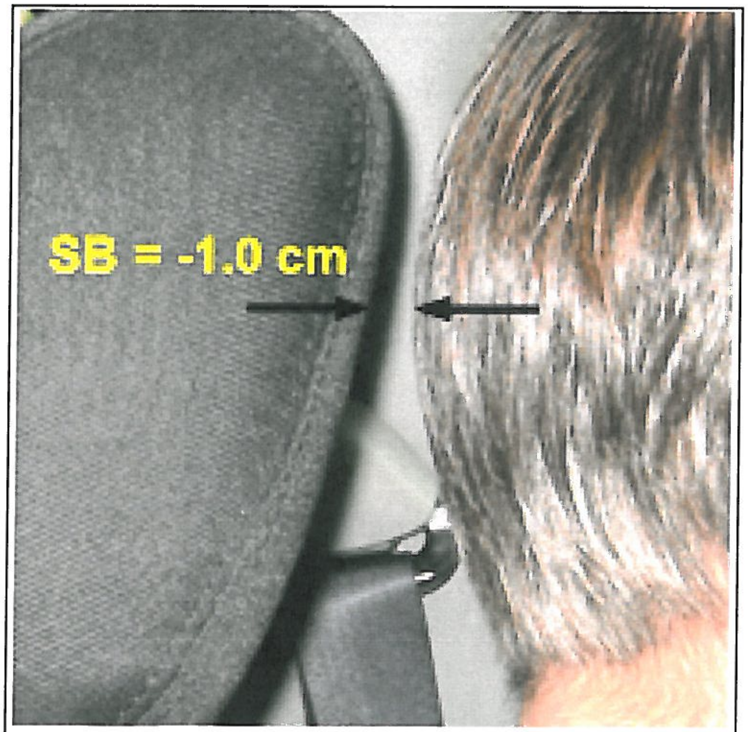

Figure 2a. Position of driver's head with vehicle parked and with driver in a self-selected, neutral head position (FHP = 0 cm; SB = -1.0 cm).

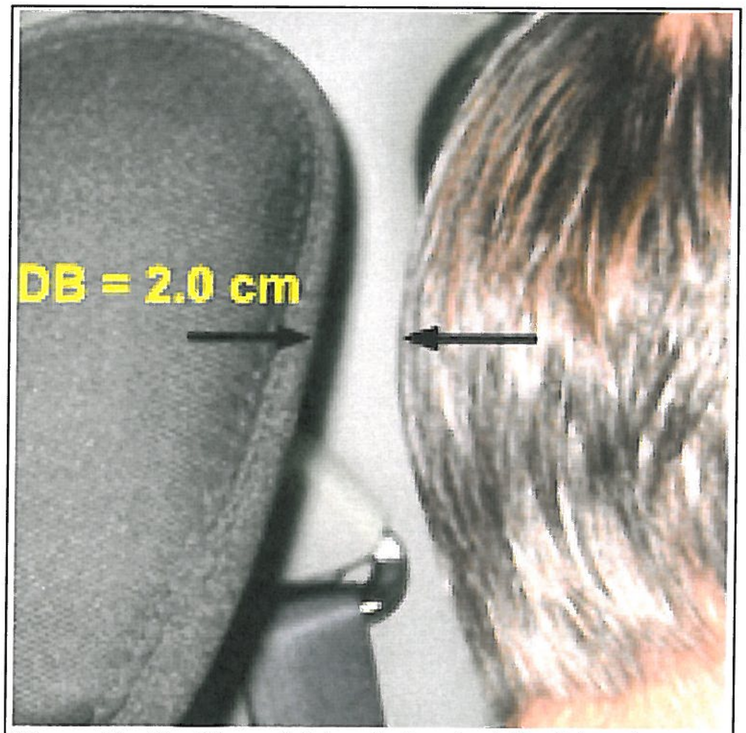

Figure 2b. Position of driver's head while driver is engaged in normal driving activities (SB = -1.0 cm; FHP = 1.0 cm; DB = 2.0 cm).

Estimation of OA Angle as a Function of Retraction/Protrusion of the Driver's Head

There is significant variation in morphologic and kinematic characteristics among individuals. Physical parameters of the proposed model, representative of a general population, were derived from data obtained from peer-reviewed scientific journals. Figure 3 shows the orientation of C0 (occiput), C1 (atlas), and C2 (axis) with the head in full protrusion, neutral, and full retraction (Penning 1978). The angle between the occiput and the posterior arch of C1 with the head in full protrusion was estimated to be equal to 0 degrees (Penning 1978). The angle between the occiput and the posterior arch of C1, with the head in a neutral position, was estimated to be 14 degrees (Ordway et al. 1999; Hanten et al. 1991). The angle between the occiput and the posterior arch of C1 with the head in full retraction was estimated to be equal to 25 degrees (Penning 1978). The total range of physiologic, translational motion in the sagittal plane was estimated to be equal to 10.5 cm (Ordway et al. 1999; Hanten et al. 1991). The NHP was estimated to be located at a point equal to 42% of the total translational range of motion (Hanten et al. 1991). Based upon 4 samples taken from fresh head/neck specimens in our laboratory, the length of RCPMi muscles with the head in a neutral position was estimated to be equal to 3.1 cm which is in agreement with published findings (Kamibayashi and Richmond 1998; Borst et al. 2011). Figure 4 shows a plot of estimated OA angle as a function of voluntary protrusion/retraction of the head. The NHP coincides with a FHP = 0 and an OA angle = 14 degrees. The model estimates that the posterior arch of C1 will come into contact with the spinous process of C2 at an OA angle of 35 degrees.

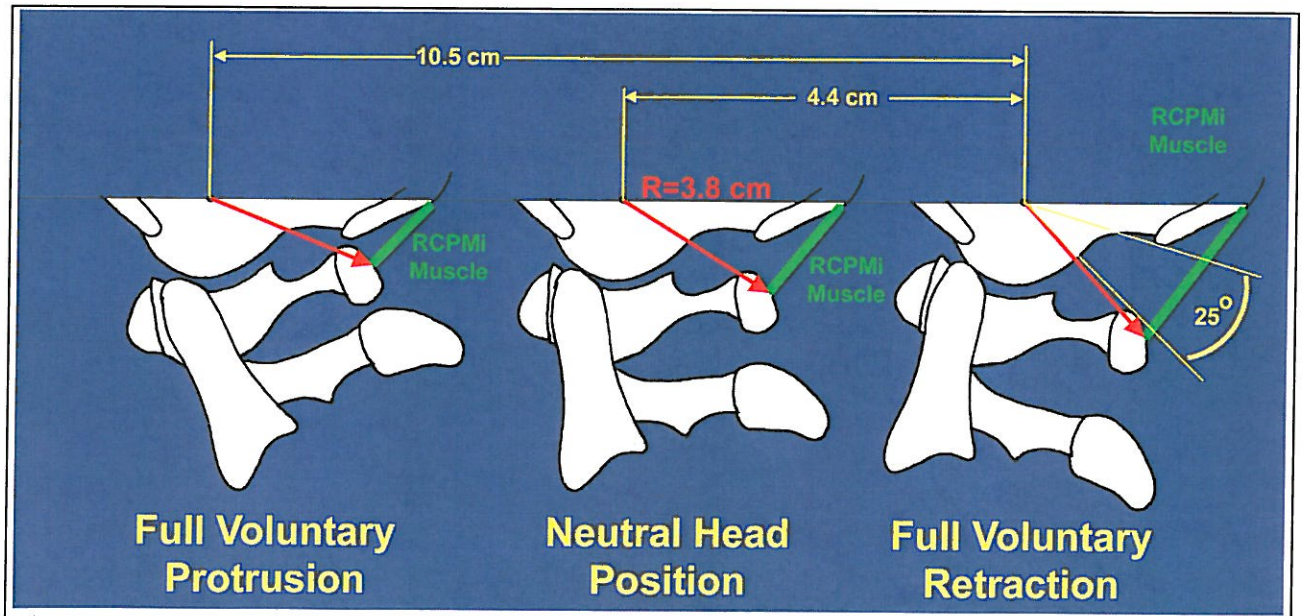

Figure 3. Orientation of C0, C1, and C2 with the head in full voluntary protrusion, neutral, and full voluntary retraction.

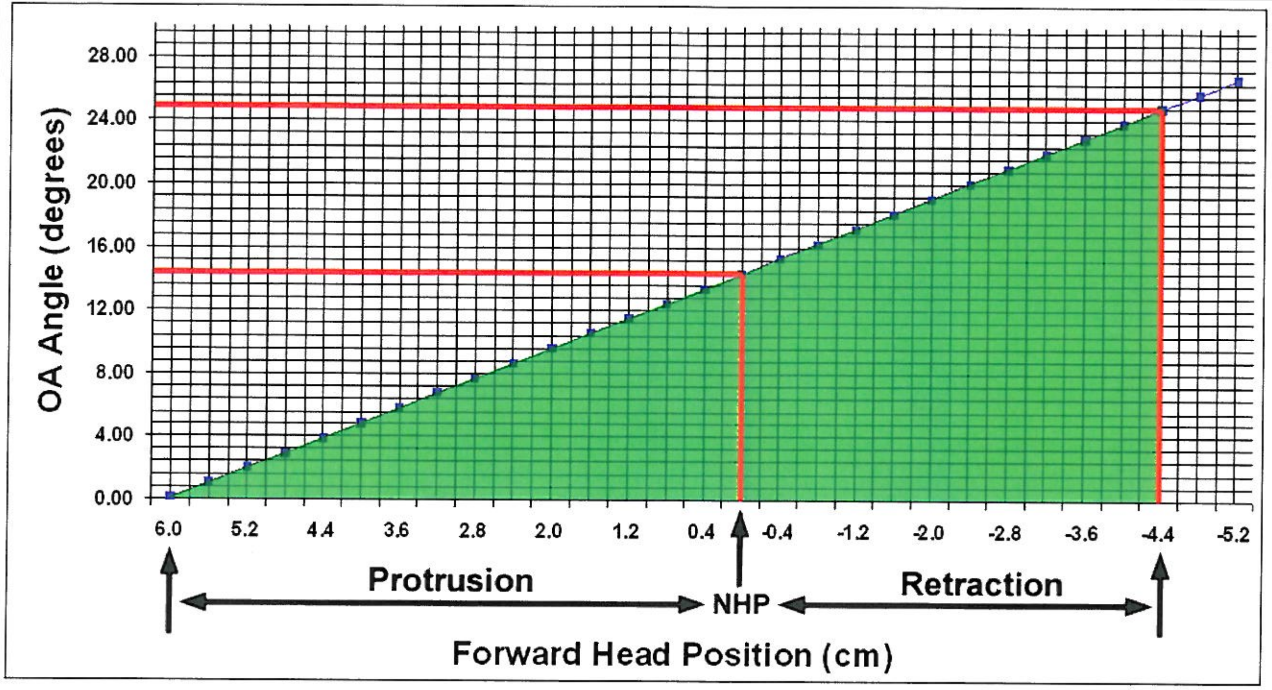

Figure 4. Estimate of OA joint angle as a function of forward head position (FHP). Green shading indicates physiologic motion. OA Angle = 14.35 – 2.38*FHP; R-squared = 0.999.

Estimation of Change in RCPMi Muscle Length as a Function of Change in OA Joint Angle

The following equation provides an estimate of the change in RCPMi muscle length (L) as a function of the change in OA joint angle (α). This calculation is based upon the assumption that the line of action of the RCPMi muscles in the general population is tangential to the arc of motion of the posterior arch of C1 (Van Mameren et al. 1990). It is understood that this equation is only an approximation of the change in muscle length as a function of OA joint angle. The error between the actual length and the calculated length is estimated to be less than 3%.

$L = 2*R*\sin(\alpha/2)$ = Estimated change in length (cm) of RCPMi muscles as a function of change in OA joint angle (degrees).

Where: R = is the distance measured from the origin of the axis of rotation of C1 about C0 to the attachment point on C1 of the RCPMi muscle (See Figure 5).

α = change in OA joint angle defined as the difference between the joint angle at the time of impact and the joint angle at the time when the subject's head strikes the head restraint.

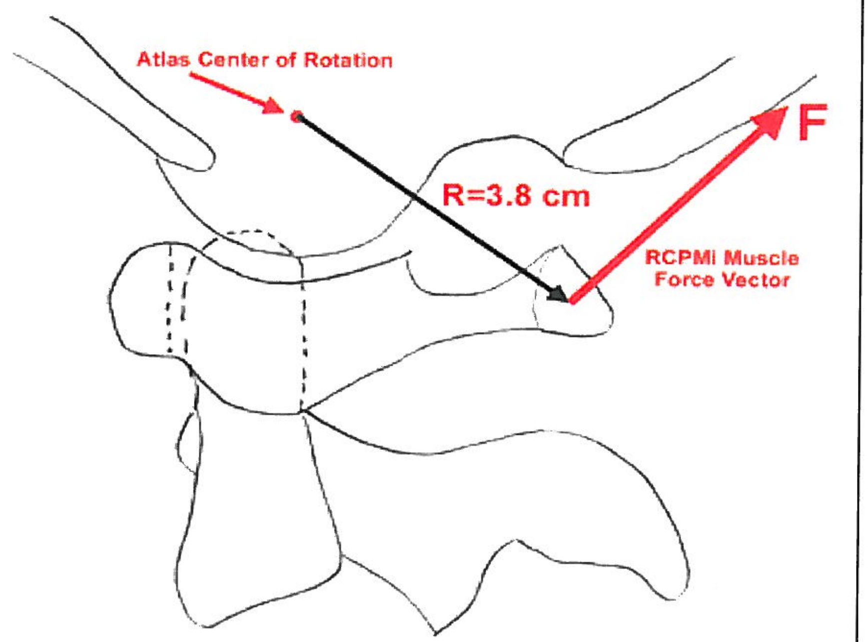

Figure 5. Axis of rotation of the posterior process of C1 about C0.

R is estimated to be equal to 3.8 cm (Konig et al. 2005). The amount of posterior translation of the head with respect to C1 as a result of physiologic motion is by necessity small (<3 mm) to avoid injury to the spinal cord (Oda et al. 1991; Garrett et al. 2010). Apart from disruption of ligamentous tissues, R is not expected to change significantly for horizontal translation of the head with respect to T1 during the retraction phase of a REMVA.

Estimation of Biomechanical Properties of RCPMi Muscle

Muscles are made up of fascicles and tendons both of which are non-homogeneous and have non-linear, viscoelastic properties (Maganaris 2002). Fascicle compliance is typically greater than tendon compliance (Trestik & Lieber 1993), and the compliance of both change with length and rate of stretch. Very little is known about the specific biomechanical properties of RCPMi muscles. Consequently, estimates of RCPMi properties will be based upon comparisons with muscles having a similar size and function, and from unpublished data from our laboratory.

Lower limb muscles, such as the gastrocnemius with a tendon to fascicle length ratio of 11 (Hoang et al. 2007), utilize tendons to store and released energy during activities such as walking and running (Lichtwark 2008). Approximately 1/2 of the total change in length of the gastrocnemius muscle during walking is due to change in the tendon length. For cervical muscles such as the iliocostalis cervicis, the ratio of tendon to fascicle length is approximately 12. The ratio of tendon to fascicle length decreases in shorter cervical muscles. On the average, the ratio of tendon to fascicle length in deep cervical multifidus is estimated to be 1.0 (Anderson et al. 2005), and the ratio in digital flexors is estimated to be 2.9 (Ward et al. 2006). In contrast to lower limb muscles, muscles with tendon to fascicle length ratios closer to 1 are hypothesized to function as stabilizers (Ward et al. 2009) and for precise position control (Ward et al. 2006). There is a significant variation in tendon stiffness among muscles. Stiffer tendons are able to transfer muscle forces more rapidly, and increased stiffness results in lower values of strain (Pearson et al 2007). Values of strain range between 9% in gastrocnemius (Hoang et al. 2007) to 3% in digital flexors (Ward et al. 2006). Fascicle strain in RCPMi muscles is estimated to be 1.2 to 2.3 times larger than muscle strain (Vasavada et al. 2007).

Significant variation in muscle stiffness has also been reported. The spring constant for the extensor digitorum in rabbit is 2X the spring constant of tibialis anterior (Best et al. 1994). To account for variation in stiffness as a function of the length of the muscle, tendons and fascicles in our model were modeled as piece-wise linear springs. The spring constant for RCPMi muscles over the range of 2.8->3.1 cm was estimated to be equal to 50 N/cm, and equal to 80 N/cm over the range of 3.1->4.09 cm for a stretch rate of 24.5 cm/s (Unpublished data Hallgren 2011). Stiffness of the tendon was estimated to be 5X larger than fascicle stiffness. No attempt was made in the model to account for nonlinearities due to the aponeurosis (Maganaris 2002) or to time dependent properties.

Results

Table 1 shows the magnitude of RCPMi muscle strain (%), as a function of static backset (SB) and the driver's forward head position (FHP) while driving, that would occur in a REMVA by the time that the driver's head makes contact with the head restraint. A magnitude of strain greater than 35% would be expected to result in injury at the musculotendonous junction of RCPMi muscles (Garrett et al. 1988; Sun et al. 1998; Tsang et al. 1998; Brooks and Faulkner 2001; Davis et al. 2003; Hallgren et al. 2011 unpublished data). Green values indicate magnitudes of strain ≤ 35%. Red values indicate strain magnitudes > 35%.

	FHP (cm)										
	Protrusion							NHP	Retraction		
SB (cm)	5.0	4.8	4	3.2	2.4	1.6	0.8	0	-0.8	-1.6	-2.4
0	42%	35%	27%	21%	15%	9%	5%	0%			
-2	57%	49%	41%	34%	27%	21%	16%	11%	6%	2%	
-4	73%	63%	54%	46%	39%	33%	28%	21%	16%	12%	8%
-6	88%	78%	68%	59%	52%	44%	40%	32%	27%	22%	17%
-8	103%	92%	82%	72%	64%	56%	51%	43%	37%	32%	27%

Table 1. Magnitude of RCPMi muscle strain (%), as a function of static backset (SB) and the driver's forward head position (FHP) while engaged in normal driving activities, that would occur in a REMVA by the time that the driver's head makes contact with the head restraint. Green values indicate magnitudes of strain ≤ 35%. Red values indicate strain magnitudes > 35%.

Discussion

Little has been published that addresses kinematics and risk of injury to structures of the upper cervical spine. Cervical facet joints in the lower cervical spine and cervical ligaments (CL) have been implicated as potential sources of head and neck pain resulting from whiplash injuries (Fice et al. 2011). However, evidence of microstructural damage has not been detected using standard clinical imaging techniques (Quinn and Winkelstein 2011).

Our computational model reveals that the risk of strain injury to the RCPMi muscles is directly related to the maximum amount of total head translation (DB = FHP - SB) that could occur at the time of impact. It has been reported that both males and females will reposition their head forward while engaged in normal driving activities an average of 3-4 cm from where their head would be positioned while sitting in a stationary vehicle with their head in a self-selected neutral head position (NHP) (Jonsson et al. 2008). Protrusion of the head away from the head restraint while driving increases the amount of total head translation (DB). For values of DB approaching 8 cm, the model confirms that a strain injury can occur before the driver's head strikes the head restraint. The model estimates that the risk of strain injury will be reduced for values of DB ≤ 5 cm. This is slightly more conservative than the value of 5.5 cm suggested by the National Highway Safety Administration (National Highway Safety Administration, 2007) and significantly more conservative than the value of 7.0 cm suggested by the Research Council for Automotive Repair (RCAR 2008) for their category of "good" head restraint geometry. A recent study, using an ultrasonic measurement device, measured an average DB of 7.8 cm (SD 24.8) for male and female drivers over a predetermined driving route (Shugg et al. 2011). Voluntary retraction of the head while driving would not be common but would be expected to reduce the risk of strain injury.

Studies have shown that females have about twice the risk of sustaining whiplash injuries than do males (Berglund, 2002). It has been reported that females, matched with males by standing height and neck length, have a significantly smaller external neck size and lower neck strength (Vasavada et al. 2008), and that female neck muscles have consistently smaller cross-sectional areas than males have (Ulbrich et al. 2011). A ratio of about 0.5 for female-to-male physiologic cross-sectional area (PCSAs) of RCPMi muscles has been reported (Kamibayashi and Richmond 1998). For a given applied force, the strain developed within a passively stretched muscle will be inversely related to the PCSA of the muscle. Consequently, based upon differences in female-to-male PCSAs, strain in RCPMi muscles resulting from a REMVA would be expected to be greater in females than in males. This, along with statistically significant increased values of retraction in surprised vs. alerted female subjects (Siegmund et al. 2008), could account for the increased incidence of whiplash injuries that are seen in females.

It would be reasonable to expect that muscles at the levels of C2, C3, and C4 could also be vulnerable to similar types of strain injuries. Patients suffering from persistent whiplash-associated disorders have demonstrated significant amounts of FI on MRI at these levels (Elliot et al. 2006). It has been reported that cervical levels C3/C4 are where flexion of the upper cervical spine transitions to extension in the lower cervical spine during a REMVA (Cusick et al. 2001). Consequently, a more sophisticated model might also predict hyperflexion injuries in muscles at the these levels.

While the specific biomechanical properties of RCPMi muscles are poorly known, it is accepted that the morphological and biomechanical properties of muscles are optimized to perform specific tasks (Lieber and Ward 2011). Clinical anatomy textbooks typically report that bilateral contraction of the RCPMi muscles causes backward bending of the head. We hypothesize that the small size of the muscles in comparison with the posterior extensors and the high density of muscle spindles in RCPMi muscles (Peck et al. 1984; Kulkarni et al. 2001) suggests that the role of RCPMi muscles is to work together with rectus capitis anterior (RCA) muscles to control forward and backward bending of the atlas in order to maintain optimal congruence of the superior articular surfaces of the atlas with respect to the occipital condyles under the varying conditions of loading of the occipitoatlantal joints that occur during flexion and extension of the head and neck. FI of RCPMi muscles reduces muscle volume leading to a loss of strength and a loss of proprioceptive feedback from muscle spindles. Loss of proprioceptive feedback from RCPMi muscles would interrupt CNS control strategies to accurately position the head and neck leading to decreased head and neck repositioning accuracy (Sjolander et al. 2008), changes in head and neck positioning patterns (Revel et al. 1991; Heikkila et al. 1996; Feipel et al. 2006), decreased range of motion (ROM), and dizziness (Nordin et al. 2008). Patients with cervicogenic headache often assume an exaggerated forward positioning of the head. While this serves to reduce tension within the RCPMi muscles, it results in abnormal stresses being imposed upon the rest of the cervical spine that may contribute to the maintenance of head and neck pain (Haughie et al. 1995).

The study has many limitations. The specific biomechanical properties of RCPMi muscles are poorly known and the compliance of these muscles would most likely vary as a function of head position and rate of stretch. The impact that soft tissues, such as the obliquus capitis superior (OCS) muscles, acting in parallel with RCPMi muscles, would have upon the dependent variables is unknown, but is considered to be small due to the location of their attachments, which are lateral and anterior to those of the RCPMi muscles. Wide variations in morphologic and kinematic properties of the upper cervical spine, along with variations of architectural properties among muscles, make it challenging to define absolute levels of strain that would result in injury at the musculotendonous junction of RCPMi muscles among the general population (Garner and Pandy 2003).

Summary

This is the first time that a computational model has predicted injury to a structural component of the upper cervical spine that would account for pathology that is detectable on standard clinical diagnostic MRI and seen in some whiplash patients suffering from chronic head and neck pain. Early detection of pathology has the potential to guide treatment strategies that would lessen the rate of transition for some individuals from an acute to a chronic condition. (Speer et al. 1993).

The model indicates that risk of a strain injury to the musculotendonous junction of RCPMi muscles is directly related to the dynamic backset (DB) during the retraction phase of a REMVA, and that the magnitude of this strain can be of sufficient magnitude to exceed injury thresholds, resulting in pathology that is accompanied by FI of the muscle. The model indicates that FHP is more important as a predictor of risk of injury than is SB. For a given value of muscle strain associated with a SB with FHP = 0, the value of muscle strain associated with the same value of FHP with SB is 28% higher. In order to minimize risk of injury to the RCPMi muscles during a REMVA, the head restraint should be adjusted when the vehicle is stationary to minimize the distance between the driver's head, and the driver should minimize protrusion of their head while driving to limit post impact, total head translation to less than 5 cm.

Future work will address the functional significance of RCPMi muscles and the presence/absence of a strain injury to these muscles on MRI following a REMVA.

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