Abstract: Chin tuck is a physiologic motion involving posterior translation of the head within a sagittal plane without rotation that results in flexion of the occipito-atlantal (OA) joint and stretching of the rectus capitis posterior minor (RCPm) muscles. While chin tuck has been shown to significantly reduce headache frequency and intensity, it is not known why stretching of RCPm muscles might be associated with resolution of head and neck pain. Three-dimensional, computer-based biomechanical models use detailed anatomic data to characterize musculoskeletal anatomy and kinematics. Modeling the length-tension properties of RCPm muscles during chin tuck would help clarify its functional significance and its role in treating head and neck pain. The objective of this study was to investigate length-tension properties of RCPm muscles during a voluntary retraction of the head (chin tuck) using a biomechanical model of the OA joint. Length-tension properties of RCPm muscles have not been previously modeled. Skeletal morphology of C0 and C1 was defined using a commercial 3-dimensional data set. The instantaneous axis of rotation of C0/C1 was estimated from flexion/extension studies. Optimal fascicle length, pennation angle, cross sectional area, and orientation of the atlas with respect to the occiput were obtained from published data. The model documents that length-tension properties of RCPm muscles are significantly affected by variations in the morphological properties of the musculotendinous unit. Use of this model would help clarify the negative impact that RCPm muscle pathologies might have upon posture and the performance of normal daily activities.
Gwendolen Jull, Editor  
Manual Therapy  

Dear Dr. Jull:  

I would like to submit the manuscript entitled, “Modeling Length-Tension Properties of RCPm Muscles During Voluntary Retraction of the Head (Chin Tuck)”. The work is original and has not been previously published or is it currently submitted to another journal. I confirm that I have had full access to all the data in the study and that I take responsibility for the integrity of the data and the accuracy of the data analysis as well as the decision to submit for publication.  

The purpose of this study was to develop a 3-dimensional, biomechanical model of the occipitoatlantal joint that would characterize length-tension properties of RCPm muscles during voluntary retraction of the head with respect to thoracic vertebra T1. Use of this model would help clarify the negative impact that RCPm muscle pathologies might have upon posture and the performance of normal daily activities. This is the first time that a biomechanical model characterizing the length-tension response of RCPm muscles during voluntary retraction of the head in a sagittal plane has been developed.  

Sincerely yours,  

Richard Hallgren, Ph.D.  
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Michigan State University  
East Lansing, MI  48824  
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Modeling Length-Tension Properties of RCPm Muscles During Voluntary Retraction of the Head (Chin Tuck)

Richard C. Hallgren, Ph.D.\textsuperscript{1,2}

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

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

Address correspondence and reprint requests to Richard Hallgren, PhD, Department of Physical Medicine & Rehabilitation, 909 Fee Road, Michigan State University, East Lansing, MI 48824; E-mail: hallgren@msu.edu, Phone: 517-355-4674, Fax: 517-432-1339.
Chin tuck is a physiologic motion involving posterior translation of the head within a sagittal plane without rotation that results in flexion of the occipito-atlantal (OA) joint and stretching of the rectus capitis posterior minor (RCPm) muscles. While chin tuck has been shown to significantly reduce headache frequency and intensity, it is not known why stretching of RCPm muscles might be associated with resolution of head and neck pain. Three-dimensional, computer-based biomechanical models use detailed anatomic data to characterize musculoskeletal anatomy and kinematics. Modeling the length-tension properties of RCPm muscles during chin tuck would help clarify its functional significance and its role in treating head and neck pain. The objective of this study was to investigate length-tension properties of RCPm muscles during a voluntary retraction of the head (chin tuck) using a biomechanical model of the OA joint. Length-tension properties of RCPm muscles have not been previously modeled. Skeletal morphology of C0 and C1 was defined using a commercial 3-dimensional data set. The instantaneous axis of rotation of C0/C1 was estimated from flexion/extension studies. Optimal fascicle length, pennation angle, cross sectional area, and orientation of the atlas with respect to the occiput were obtained from published data. The model documents that length-tension properties of RCPm muscles are significantly affected by variations in the morphological properties of the musculotendinous unit. Use of this model would help clarify the negative impact that RCPm muscle pathologies might have upon posture and the performance of normal daily activities.
1. Introduction

Voluntary retraction of the head, with respect to thoracic vertebra T1, (chin tuck) is a physiological motion that results in posterior translation of the head without rotation within a sagittal plane (Penning, 1978; Penning, 1992). The amount of posterior translation of the head relative to C1 is by necessity small (<3 mm) to avoid injury to the spinal cord (Oda et al., 1991; O’Brien and Sutterlin, 1996; Garrett et al., 2010). Consequently, translation of the head also results in translation of cervical vertebra C1, coupled with flexion of the occipito-atlantal (OA) joint and stretching of rectus capitis posterior minor (RCPm) muscles.

RCPm 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. RCPm muscles are the only muscles that attach to the posterior arch of C1 (Clemente, 1995). While the functional role of RCPm muscles has not been clearly defined, bilateral contraction of RCPm muscles is purported to result in extension of the head. It is accepted that the morphological and biomechanical properties of muscles are optimized to perform specific tasks (Lieber and Ward 2011). Consequently, the small size of RCPm muscles, relative to larger muscles acting in parallel with them, would minimize their contribution to gross extension of the head and neck (Nitz and Peck, 1986; Nolan and Sherk, 1988). Normalized levels of EMG activity in RCPm muscles have been shown to significantly increase as asymptomatic subjects move their head from a self-selected neutral head position (NHP) to a retracted head position (RHP) (Hallgren et al, 2013) suggesting that chin tuck exercises should both stretch and strengthen RCPm muscles.

Biomechanical models of the cervical spine have been used to complement experimental studies by estimating tissue strain and strain rates that are difficult, if not impossible, to measure in vivo. Many studies have used biomechanical models to investigate the kinematic response of the cervical spine to simulated rear end motor vehicle collisions (REMV) (Grauer et al., 1997; Vasavada et al., 2007). Almost without exception, previous studies have focused upon structures associated with cervical vertebrae C2–C7.

Head posture, specifically a forward head posture (FHP), is one of several postural characteristics that are associated with head and neck pain (Fernandez-de-las-Penas et al., 2006; Szeto et al., 2002). Development of a biomechanical model of C0, C1, and RCPm muscles would help us to better understand both the functional role of RCPm muscles in the performance of daily activities, and the negative impact that RCPm muscle pathologies might have upon posture and the performance of normal daily activities. A biomechanical model characterizing
the length-tension response of RCPm muscles during voluntary retraction of the head has not been previously developed.
2. Methods

A 3-dimensional model of the human skull (C0), the atlas (C1), and RCPm muscles was implemented in OpenSim (http://opensim.stanford.edu) (Delp and Loan, 1995; Vasavada et al., 1998). The skeletal morphology of the model was defined using a commercial 3-dimensional data set of C0 and C1 (TurboSquid, New Orleans, LA). The instantaneous axis of rotation (IAR) for C0/C1 was estimated from flexion/extension studies (White and Panjabi, 1978); Fig. 1. Because of the unique anatomy and biomechanics of the OA joint, studies usually do not attempt to quantify the location of the IAR of C0/C1 (Amevo et al., 1991), and when they do there is significant error due to random effects as well as dispersions due to morphological variations (van Mameren et al., 1992).

The total head excursion (THE), from full voluntary protrusion to full voluntary retraction with respect to T1 in the sagittal plane without rotation, has been reported to be 10.7 (2.5) cm (Hanten et al., 1991). They estimated that the neutral head position (NHP) is located at a point that is 45.2% of THE, measured in an anterior direction from the point of full voluntary retraction of the head. Using these values, we estimated that the NHP position could be estimated to be located 4.8 cm anterior to the point of full voluntary retraction; Fig. 1.

When the head is held in a neutral position, the angular displacement of C1 with respect to C0 has been estimated to be 19.4 degrees (Orday et al., 1999). As the head moves to a fully retracted position this angle is estimated to increase to 25 degrees (Orday et al., 1999); Fig. 1.

Fig. 1. Orientation of C0 and C1 with the head held in a self-defined neutral position and in full voluntary retraction (Orday et al., 1999; Hanten et al., 2000).
The attachment sites of RCPm muscle in the model were defined relative to known anatomic landmarks (Clemente, 1995; Kamibayashi and Richmond, 1998) using the editing capabilities of OpenSim. The muscles were approximated by straight lines directed from the posterior tubercle of the posterior arch of C1 to the occipital bone inferior to the inferior nuchal line and lateral to the midline. It was assumed that errors due to the effects of wrapping surfaces would be minimal (Suderman and Vasavada, 2012).

OpenSim uses a generic musculotendonous model that accounts for the static properties of both muscle and tendon and computes musculotendon force as a function of musculotendon length (Bern and Levy, 1998; Delp et al., 1990); Fig. 2. Muscles are modeled by parallel active and passive components of muscle fascicles, which are in series with tendon. Muscle fascicles were assumed to have properties that are similar to the force-length properties of muscle fibers (Vasavada et al., 2007).

The parameters used to scale the generic model to represent the force-length characteristics of the RCPm musculotendonous unit are optimal fiber length (OFL), maximum isometric force (MIF), pennation angle (PA), and tendon slack length (TSL). MIF for RCPm muscles can be estimated from the physiologic cross sectional

![Normalized Force-Length Curve](image)

Fig. 2. The normalized force-length curve of RCPm muscles scaled by the optimal fascicle length and the peak isometric muscle force (Bern and Levy, 1998; Delp et al., 1990).
area (PCSA) (Zajac, 1989). PCSA can be significantly affected by measurement methods and differences in
maximum strength within age groups (Van Ee et al., 2000; Hakkinen and Hakkinen, 1991). Van Ee et al. (2000)
reported that 50th percentile muscle volumes estimated from MRI of living humans were 63% larger than
cadaveric volumes obtained by dissection (Kamibayashi and Richmond, 1998), supposedly as a result of
premortem atrophy and postmortem dehydration. In this study, PCSA for RCPm muscles was defined as the
mean of values reported by Van Ee et al. (2000) and Kamibayashi & Richmond (1998). MIF can be estimated
by multiplying PCSA by a peak force scaling factor (SF) that can vary from 35 – 55 N/cm² in the human
(McGill and Norman, 1986). Vasavada et al. (1998) used the lower value primarily to compensate for the
decreased muscle size in their elderly cadavers. We wanted our model to better represent a younger cross section
of the general population and set SF to the mean value reported by McGill and Norman (1986). Table 1 shows a
summary of modeling parameters for RCPm muscles along with either the reference of their source or the
equation that was used to calculate the parameter.

<table>
<thead>
<tr>
<th>Model Parameters</th>
<th>Value per RCPm Muscle</th>
<th>Source</th>
</tr>
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<tbody>
<tr>
<td>Musculotendonous Length (MTL)</td>
<td>2.85 cm</td>
<td>Kamibayashi &amp; Richmond, 1998</td>
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<td>Pennation Angle (PA)</td>
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<tr>
<td>Muscle Fascicle Length (MFL)</td>
<td>1.7 (0.2) cm</td>
<td>Kamibayashi &amp; Richmond, 1998</td>
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<td>Optimal Sarcomere Length (OSL)</td>
<td>2.70 µm</td>
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<td>Muscle Sarcomere Length (MSL)</td>
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<td>Optimal Fascicle Length (OFL)</td>
<td>1.81 cm</td>
<td>OFL = MFL*(OSL/MSL)</td>
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<td>Tendon Slack Length (TSL)</td>
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<td>TSL = MTL – OFL</td>
</tr>
<tr>
<td>Physiologic Cross Sectional Area (PCSA)</td>
<td>0.71 cm²</td>
<td>Van Ee et al., 2000</td>
</tr>
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<td>Peak Force Scaling Factor (SF)</td>
<td>45 N/cm²</td>
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<td>Maximum Isometric Force (MIF)</td>
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Table 1. Summary of modeling parameters for RCPm muscles in NHP.
3. Results
The normalized fascicle length of RCPm muscles, as a function of head position, was found to be consistent with reported data for posterior cervical extensors such as splenius capitis (Vasavada et al., 1998); Fig. 3. Fascicle length changes during retraction of the head from a NHP to the RHP were found to be equal to 33% of the optimal fascicle length. The ratio of TSL to OFL was equal to 0.68 and the ratio of OFL to the average length of the moment arm varied from 0.61 to 0.81, both consistent with published values (Winter and Challis, 2010).

Fig. 3. Fascicle length of RCPm muscles as a function of head position superimposed upon a normalized force-length curve. Heavy vertical line indicates fascicle length at the NHP.

Translation of the head from the NHP to the RHP was found to decrease the length of the moment arm from 2.8 cm to 2.1 cm, values that are consistent with published data (Dugailly et al., 2011; Vasavada et al., 1998). The moment generating capacity of a single RCPm muscle was found to decrease from 0.5 NM to 0.365 NM, partly
due to the decrease in the length of the moment arm and partly due to the decrease in the maximum isometric muscle force that RCPm muscles could produce at a length associated with the head in the RHP.

A sensitivity analysis was performed to determine the influence of variability in modeling parameters. Kamibayashi & Richmond (1998) reported muscle fascicle lengths of 1.7(0.2) cm; Table 2. Varying the fascicle length at the NHP by one standard deviation in each direction resulted in a change of approximately ±15% in both the maximum active force and the moment generating capacity that could be produced by the RCPm muscles with the head positioned at the RHP.

<table>
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<tr>
<th>Fascicle Length (NHP)</th>
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<th>Moment Arm (RHP)</th>
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Table 2. Sensitivity analysis performed to determine the influence of variability in fascicle length.

4. Discussion

The current model demonstrates that length-tension properties of RCPm muscles are significantly affected by normal variations in morphological properties of the musculotendinous unit. Shortening of the fascicle length reduces the capability of these muscles to generate normal levels of active force with the head in the RHP, while increasing the magnitude of passive forces imposed upon the fascicle-tendon complex. Changes in the properties of the musculotendinous unit due to pathologies such as fatty infiltration of RCPm muscles would also be expected to reduce the capability of these muscles to generate forces necessary to enable the performance of daily activities without altering normal posture.

Rear end motor vehicle collisions (REMVC) can result in forced retraction of the head (as opposed to voluntary retraction of the head) with respect to thoracic vertebra T1 (Cholewicki et al., 1998)). Within a short period of time, the driver’s head moves in a posterior direction without rotation until the head-restraint is reached. Increased distance between the head and the head restraint at the time of impact is thought to result in increased risk for sustaining a whiplash-type injury (Carlsson et al., 2011). When the head-to-head restraint distance exceeds ~ 4.8 cm, non physiologic flexion of the OA joint occurs (Hanten et al., 2000), resulting in elevated values of musculoskeletal strain within RCPm muscles. Values of musculoskeletal strain that exceed critical levels are known to result in structural damage to the musculotendinous junction (Garrett et al., 1988) that results in fatty infiltration (FI) of the muscle (Beeler et al., 2013). Studies have demonstrated significant amounts of FI on magnetic resonance images (MRI) in RCPm muscles of patients suffering from persistent
whiplash-associated disorders (WAD) (Hallgren et al., 1994; Andary et al., 1998; Elliott et al., 2006). 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., 2008). 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., 2005). Fatty infiltration of RCPm muscles on MRI has been shown to be related to chronic headache intensity, duration, or frequency (Fernandez-de-las-Penas et al., 2007). While the cause of the fatty infiltration in these patients is unknown, it has been reported that headache intensity, duration, and frequency increase as the cross sectional area of the muscles decreases (Fernandez-de-las-Penas et al., 2007), and that the progression of fatty infiltration over time is directly related to pain and disability (Elliott, 2011). Whether these instances of FI are a primary or secondary phenomenon remains unclear. Fatty infiltration would be expected to result in changes in both the active and passive characteristics of the muscle. The loss of functional capability/capacity would compromise the ability of these muscles to achieve normal levels of force necessary for the performance of daily activities as a result of mechanical impairment and/or loss of proprioceptive components.

Recent studies have shown that RCPm muscles are active at an average level of 11.9% of maximum voluntary isometric contraction (MVIC) when the head is held in a self-selected NHP, and that activity increases to an average level of 31.9% of MVIC when the head is voluntarily retracted (Hallgren et al., 2013). An eccentric muscular contraction occurs when forces generated by the muscle are insufficient to overcome the load placed upon the muscle. As a result, the muscle is forced to lengthen as it contracts. Eccentric exercises are known to enhance muscle size, strength, and composition (McArdle et al., 2001; Blazevich et al., 2007). This suggests that one benefit of chin tuck exercises would be to both stretch and strengthen RCPm muscles.

5. Limitations
The study has many limitations. Significant variations regarding the shape, size and morphology of the OA joint and the physical characteristics of RCPm muscles complicate the process of creating a biomechanical model that accurately represents a general population. For example, morphological variations in the shape of the superior articular facets have been categorized among specimens according to shape as oval, kidney, S-like, eight-like, triangle, circular, and two-portioned facets (Singh, 1965; Paraskevas et al., 2008), and bilateral comparisons within specimens show a significant difference between metrics such as the width, length, and depth of the superior facet (Meseke et al., 2008; Gottlieb, 1994). The same significant variations apply to the occipital condyles. Similar morphological variations have been reported for all structures of the OA joint.
(Kamibayashi and Richmond, 1998; Van Ee et al., 2000; Vasavada et al., 1998; Borst et al., 2011) and would be expected to increase variability to an unknown extent.

6. Conclusions

The model presented in this paper demonstrates that normal variations in morphological properties of the musculotendinous unit will have an impact upon the moment generating capability of RCPm muscles. The model suggests that variations in the cross-sectional area of RCPm muscles due to pathologies such as fatty infiltration will reduce the ability of these muscles to generate levels of force that are consistent with forces generated in asymptomatic subjects. The inclusion of chin tuck exercises in a treatment regiment intended to reduce headache frequency and intensity might provide benefit to patients by facilitating the resolution of postural problems such as FHP that may be a consequence of shortened and weakened RCPm muscles.
References


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Suderman BL, Vasavada AN. Moving muscle points provide accurate curved muscle paths in a model of the cervical spine. J Biomech 2012;45(2):400-404.


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Figure 3

Active Fiber Force (N) vs. Normalized Fascicle Length

Head Retraction (cm)

-1.0 -0.25 -3.0 -4.5
Figure Legends

Fig. 1. Orientation of C0 and C1 with the head held in a self-defined neutral position and in full voluntary retraction.

Fig. 2. The normalized force-length curve of RCPm muscles scaled by the optimal fascicle length and the peak isometric muscle force.

Fig. 3. Fascicle length of RCPm muscles as a function of head position superimposed upon a normalized force length curve. Heavy vertical line indicates fascicle length at the NHP.