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Three-Dimensional Isometric Strength of Neck Muscles in Humans

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Study Design. Three-dimensional moments were measured experimentally during maximum voluntary contractions of neck muscles in humans.

Objectives. To characterize the maximum moments with attention paid to subject size and gender, to calculate moments at different locations in the neck, and to quantify the relative magnitudes of extension, flexion, lateral bending, and axial rotation moments.

Summary of Background Data. Few studies of neck strength have measured moments in directions other than extension, and it is difficult to compare results among studies because moments often are resolved at different locations in the cervical spine. Further, it is not clear how subject size, gender, and neck geometry relate to variations in the moment-generating capacity of neck muscles.

Methods. Maximum moments were measured in 11 men and 5 women with an average age of 31 years (range, 20–42 years). Anatomic landmarks were digitized to resolve moments at different locations in the cervical spine.

Results. When moments were resolved about axes through the midpoint of the line between the C7 spinous process and the sternal notch, the maximum moments were as follows: extension (men, 52 ± 11 Nm; women, 21 ± 12 Nm), flexion (men, 30 ± 5 Nm; women, 15 ± 4 Nm), lateral bending (men, 36 ± 8 Nm; women, 16 ± 8 Nm), and axial rotation (men 15 ± 4; women, 6 ± 3) Nm). The magnitudes of extension, flexion, and lateral bending moments decreased linearly with vertical distance from the lower cervical spine to the mastoid process.

Conclusions. Moments in three dimensions were quantified with regard to subject size and location along the cervical spine. These data are needed to characterize neck strength for biomechanical analysis of normal and pathologic conditions. [Key words: human, muscle, neck, strength] **Spine 2001;26:1904–1909**

Knowledge of neck strength is important for understanding the potential relation of muscle function to pathology. Subjects with neck pain often have decreased neck strength,[1,22] and strength training is associated with a decrease in pain.[2,11] Women have a higher incidence of neck pain[16] and a poorer recovery from whiplash injury,[8] suggesting the necessity of studying gender differences in strength.

The complex multijoint kinematics of the cervical spine presents a problem for analysis of neck muscle strength because there are multiple cervical levels at which moments can be resolved. Different analyses may require knowledge of neck moments at different locations along the cervical column. For modeling purposes, the assumed intervertebral kinematics of a specific biomechanical model may define the point at which it is necessary to know maximum muscle moment. Analysis of injury or surgical intervention (*e.g.*, spinal fusion) requires knowledge of neck muscle moments at the intervertebral level where the injury or intervention occurs. Different studies of neck strength have calculated moments at different cervical levels, making it difficult to compare studies.

For these reasons, it is necessary to know how neck muscle moments vary along the cervical spine. Knowledge of three-dimensional forces and moments, along with cervical column geometry, makes it possible to evaluate moments resolved at different locations in the cervical spine.

Movements of the head and neck occur in three dimensions about axes defined anatomically as flexion–extension, lateral bending, and axial rotation. However, most previous studies of neck strength have been limited to measurement of extension moment.[10,15,17,20,21] Because each neck muscle generates moment in different proportions about all three anatomic axes,[23] dysfunction of a particular muscle may cause differences in the relative strengths in the three dimensions. A number of studies have provided measurements for flexion, lateral bending, or axial rotation moment,[2,5,13,14,18] but only one study[18] has reported moments about all three axes. The relative strengths in the three dimensions have not been calculated on an individual subject basis.

It is important to distinguish between the location (cervical level) of the axis about which moment is calculated and its three-dimensional orientation in space (*i.e.*, flexion–extension, lateral bending, or axial rotation). Only the study of Moroney et al[18] has reported the maximum moments generated by neck muscles for extension, flexion, lateral bending, and axial rotation at one specific cervical level: the C4–C5 intervertebral disc. This provides an excellent starting point for characterizing neck muscle strength in three dimensions and variations with the cervical level. The current study builds on this previous work and examines the following questions:

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Table 1. Anthropometric and Postural Data (Means and Standard Deviations) of Participants in Strength Experiment

	Age (yr)	Weight (kg)	Height (cm)	Neck Circumference (cm)	Head Circumference (cm)	Frankfort Plane* (°)	Neck Angle† (°)
All participants	31 ± 6	74 ± 12	173 ± 10	38 ± 3	57 ± 2	8 ± 5	50 ± 4
Men (n = 11)	32 ± 6	77 ± 11	177 ± 8	39 ± 2	58 ± 1	9 ± 5	50 ± 5
Women (n = 5)	30 ± 6	65 ± 10	164 ± 9	36 ± 2	56 ± 3	8 ± 6	51 ± 3

* The Frankfort plane is the angle between the horizontal and the line between the tragus of the ear and the inferior border of the orbit.[3] This angle is positive if the inferior border of the orbit is higher than the tragus of ear.
† The neck angle is the angle between the horizontal and the line between the C7 spinous process and the tragus of the ear.[4]

1. What are the maximum moments generated by neck muscles in three dimensions?
2. How do maximum moments vary with subject size and gender?
3. How do moments vary with the cervical level at which they are resolved?
4. What are the relative maximum moments for the directions of extension, flexion, lateral bending, and axial rotation, and does this change with cervical level?

This study provides answers to these questions and new data needed to understand the biomechanics of the neck musculoskeletal system in healthy subjects.

Methods

Maximum moments were recorded in 11 men and 5 women. The mean age of the subjects was 32 years for the men and 30 years for the women (Table 1). None of the subjects had a history of neck disorders. The experimental protocol was approved by the Northwestern University Institutional Review Board. All the participants in this study gave informed consent.

The participants were seated with their heads in a comfortable, upright posture and their shoulders and torso firmly restrained (Figure 1). The head was rigidly coupled to a 6-axis load cell (ATI Industrial Automation, Garner, NC) by a device with eight pads that were tightened around the head. The participants pushed against the pads in different directions to produce the desired moments: extension, flexion, axial rotation, and lateral bending. This experimental configuration allowed recording of three-dimensional forces and moments at the load cell, which could be resolved at various anatomic locations.

Anatomic landmarks were digitized with a three-dimensional localizer (FlashPoint 5000; Image-Guided Technologies, Boulder, CO) to record subject posture and to determine the points about which moments were resolved. The landmarks digitized included midline points such as the external occipital protuberance, the spinous processes of the C7 and T1 vertebral bodies, the sternal notch, the tips of the jaw and nose, the midpoint of the eyebrows, and the bilateral points such as the mastoid process, the tragus of the ear, and the inferior border of the orbit. Midline landmarks were used to verify the orientation of the midsagittal plane of the head. The sagittal plane posture was quantified by two angles relative to horizontal: the Frankfort plane and the neck angle (Table 1). The Frankfort plane is the angle between the horizontal and the line between the tragus of the ear and the inferior border of the orbit.[3] This angle is positive if the inferior border of the orbit is higher than the tragus of ear. The neck angle is the angle between the horizontal and the line between the C7 spinous process and tragus of the ear.[4]

During the experiment, moments were resolved about axes through the midpoint of the line between the C7 spinous process and the sternal notch. This point, referred to as C7–T1 and located in the upper part of the T1 vertebral body,[9] has been used in several other studies of neck strength. During postprocessing, moments were resolved at two other cervical levels: 1) the midpoint of the mastoid processes, approximately the level of the skull–C1 joint,[9] and 2) the equivalent center of rotation calculated from the intervertebral kinematics of a biomechanical model.[23] This second point, referred to as C4, is located in the C4 vertebral body, midway between the C7–T1 point and the midsagittal plane projection of the tragus of the ear. These three points were used to calculate the variation of maximum moment with vertical distance along the cervical spine.

Figure 1. Experimental setup for neck strength measurement. Headholder with pads was attached to a load cell located behind the subject's head, and thick straps restrained the shoulders and torso. Real-time feedback of three moments was provided to the subject throughout each trial.

Table 2. Comparison of Neck Strength Studies

	No. and Gender of Subjects	Point of Moment Resolution	Extension Moment	Flexion Moment	Axial Rotation Moment	Lateral Bending Moment
Berg et al [2]	17 F		23 ± 8	13 ± 5	8 ± 3	
Choi and Vanderby [5]	10 M	C4–C5	28 ± 3	18 ± 3		17 ± 3
Harms-Ringdahl and Schüldt [10]	10 F	C7-T1	29			
		mastoid	11			
Jordan et al. [13]	50 M	C7–T1	55 ± 14	30 ± 9		
	50 F	C7–T1	48 ± 15	21 ± 8		
Lee and Ashton-Miller [14]	9	C4–C5	29 ± 7	19 ± 4		
Leggett et al [15]	53 M	Thyroid cartilage	38			
	20 F		22			
Mayoux-Benhamou et al [16]	5 M, 10 F	C7–T1	53 ± 12			
Moroney et al [18]	10 M	C4–C5	30 ± 15	12 ± 7	10 ± 3	15 ± 8
	4 F	C4–C5	17 ± 7	6 ± 3	6 ± 2	8 ± 4
Pollock et al [20]	14 M, 5 F	Thyroid cartilage	34 ± 10			
Queisser et al [21]	12 M	C7–T1	60 ± 9			
Current study	11 M	C7–T1	52 ± 11	30 ± 5	15 ± 4	36 ± 8
		C4	35 ± 8	19 ± 4	14 ± 4	25 ± 6
		mastoid	24 ± 7	13 ± 3	15 ± 4	17 ± 5
	5 F	C7–T1	21 ± 12	15 ± 4	6 ± 3	16 ± 8
		C4	15 ± 8	10 ± 2	6 ± 3	10 ± 5
		mastoid	10 ± 5	6 ± 1	6 ± 3	6 ± 3

Note. Moments in Nm (mean and standard deviation) reported at the neutral position. Points of moment resolution defined in Methods except C4–C5 (center of C4–C5 intervertebral disc) and thyroid cartilage. Berg et al [2] did not define the point of moment resolution in their study. Because Leggett et al [15] and Pollock et al [20] did not explicitly define neutral position, it was assumed to be the average of the two middle positions of the range reported. The moments reported by Harms-Ringdahl et al [10] include the moment caused by the weight of the head. The moments reported by Queisser et al [21] were measured with subjects in the supine position, and the weight of the head was subtracted.
M = males; F = females.

The participants in this study generated maximum moments in six directions (extension, flexion, right and left lateral bending, and right and left axial rotation) for three trials, each lasting 3 seconds. Load cell data were sampled at 1000 Hz, and the maximum average moment was calculated over a 200-msec window. The largest moment of the trials in each direction was considered to be that participant's maximum moment. The order of the directions was randomized. During all the trials, the participants received real-time feedback on the magnitude of three-dimensional moments resolved at C7–T1. At the end of the experiment, the participants generated one maximum moment in each of the six directions to test for fatigue. This moment occasionally was the maximum of the four total trials, and the moments during these final trials were, on average, within 10% of maximum moments, suggesting that the participants were not fatigued.

For right and left lateral bending and axial rotation, moments generated to each side were compared using a paired *t* test. Comparisons between the results for male and female participants were made using an unpaired *t* test, adjusted for unequal variances if necessary.[19] The effect of participant size was evaluated by using neck circumference as an estimate of muscle size, and head mass and inertia as an estimate of the mechanical demands on neck muscles. For each participant, head mass and inertia were calculated according to anthropometric regression equations.[12,24] Maximum moments were divided by mass (strength-to-mass ratio) and by inertia (strength-to-inertia ratio). The data for moments resolved at different cervical levels were normalized by the magnitude of the moment at C7–T1 and linearly regressed according to vertical distance along the cervical column, in which C7–T1 was defined as 0 and the mastoid process defined as 1. The ratios of flexion, lateral bending, and axial rotation moments relative to extension moment were compared at three cervical levels using analysis of variance (ANOVA). For all tests, the level of statistical significance was set at a P value of 0.05.

Results

Subjects generated their greatest maximum moments for extension. The average maximum moments resolved at C7–T1 for the men were 52 ± 11 Nm for extension, 30 ± 5 Nm for flexion, 36 ± 8 Nm for lateral bending, and 15 ± 4 Nm for axial rotation (Table 2). For the men, the maximum moments were not statistically different for the two directions of lateral bending and axial rotation.

The maximum moments generated by the women were 40% to 50% of the moments generated by the men. The maximum moments resolved at C7–T1 for the women were 21 ± 12 Nm for extension, 15 ± 4 Nm for flexion, 15 ± 8 Nm for right lateral bending, 17 ± 8 Nm for left lateral bending, and 6 ± 3 Nm for axial rotation (Table 2). For the women, there was asymmetry between left and right lateral bending moments ($P = 0.04$, paired *t* test).

Participant size does not entirely explain the differences in maximum moments among the participants. There was some correlation between neck circumference and neck strength: Over all six directions, r^2 ranged from 0.3 to 0.4, with P between 0.01 and 0.04. However, when the moments were divided by head mass or inertia, the adjusted maximum moments generated by the women still were only 40% to 60% of the moments generated by the men. For example, the strength-to-mass ratio for extension moment averaged 10.1 Nm/kg for the men, whereas it was 4.3 Nm/kg for the women. Similarly, the strength-to-inertia ratio for extension moment was 0.19 Nm/(kg − cm^2) for the men and 0.08 Nm/(kg − cm^2) for the women. Over all directions, the average strength-to-mass ratio for the men was 2.1 times greater

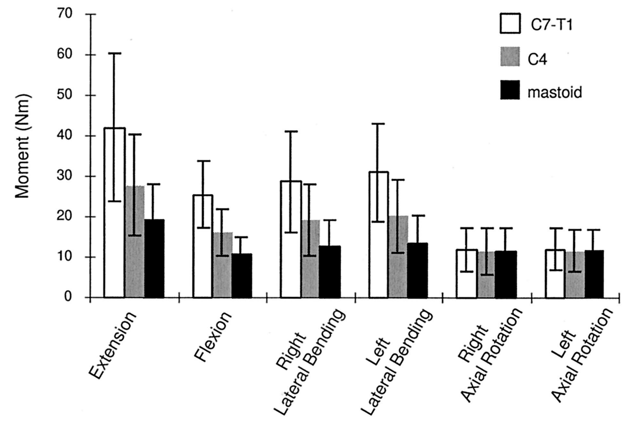

Figure 2. Effect of changing point of moment resolution. Moments were resolved at the midpoint of the line between the spinous process of C7 and the sternal notch, C4 (equivalent center of rotation of a biomechanical model),[23] and the mastoid process. The maximum moments (means and standard deviations) of 11 men and 5 women are grouped.

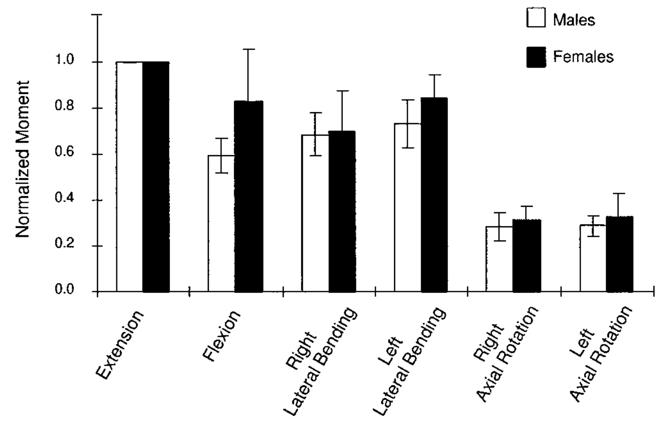

Figure 3. Maximum moments normalized to extension. Means and standard deviations for 11 men and 5 women. Moments were resolved at the midpoint of the line between the spinous process of C7 and the sternal notch.

than that for the women, whereas the average strength-to-inertia ratio for the men was two times greater than that for the women. These differences were significant in all directions ($P < 0.05$).

The cervical level at which moments were resolved affected the magnitude of maximum moments for all directions except axial rotation. For extension, flexion, and lateral bending, moments resolved at C4 were 30% to 40% lower than those resolved at C7–T1, whereas those resolved at the mastoid process were 50% to 60% lower (Figure 2). Axial rotation moments resolved to the two different locations differed by less than 5%.

Linear regression showed that extension, flexion, and lateral bending moment decreased linearly with vertical distance between C7–T1 and the mastoid process according to the following relation:

$$\frac{M}{M_{C7}} = \beta_0 - \beta_1 y, \qquad (1)$$

where M is the moment at a given cervical level, M_{C7} is the moment at C7–T1, y is the vertical distance along the cervical column ($y = 0$ at C7–T1 and $y = 1$ at the mastoid process), and β_0 and β_1 are the regression parameters (Table 3). The y intercept of the regression equation (β_0) was 1 for all moment directions. The slope (β_1) ranged between 0.5 and 0.6 for extension, flexion, and lateral bending, and was almost 0 for axial rotation (Table 3). This relation was consistent among subjects.

Calculating each participant's maximum moments in all directions relative to his or her maximum extension moment resulted in average ratios of 0.7 ± 0.2 for flexion-to-extension moment, 0.7 ± 0.1 for lateral bending-to-extension moment, and 0.3 ± 0.1 for axial rotation-to-extension moment, with moments resolved at C7–T1 (Figure 3). When the results for the men and women were analyzed separately, there appeared to be a trend for gender difference in the ratio of flexion to extension (0.6 ± 0.1 for the men and 0.8 ± 0.2 for the women). However, because of the differences in sample size and variance, the results were only marginally significant ($P = 0.048$, t test adjusted for unequal variances). The ratios of maximum lateral bending to extension moment were 0.7 ± 0.1 for the men and 0.8 ± 0.1 for the women. This difference was not statistically significant. The ratios of maximum axial rotation-to-extension moment were the same (0.3 ± 0.1) in both the men and women. Analysis of variance showed that when moments were resolved at other cervical levels, the ratios of flexion and lateral bending to extension did not change. However, because extension moment changed with the point of moment resolution and axial rotation moment did not, the corresponding ratio of axial rotation-to-extension moment changed significantly, from 0.3 ± 0.1 at C7–T1 to 0.4 ± 0.1 at C4 and 0.6 ± 0.2 at the mastoid process.

Table 3. Regression Parameters for Variation of Maximum Moment With Cervical Level: All Subject Data Pooled

	Extension	Flexion	Lateral Bending	Axial Rotation
β_1 (slope)	0.519	0.584	0.570	0.0198
95% Confidence interval	0.472–0.566	0.549–0.618	0.5695–0.5697	0.0196–0.0200
β_0 (intercept)	0.997	0.996	0.9977	0.9956
95% Confidence interval	0.966–1.029	0.973–1.019	0.9977–0.9978	0.9955–0.9958
R^2	0.920	0.965	0.934	0.077

Note. Regression parameters for the equation $M/M_{C7} = \beta_0 - \beta_1 y$, where M is the moment at a given cervical level, M_{C7} is the moment at C7–T1, and y is the vertical distance along the cervical column (y = 0 at C7–T1 and y = 1 at the mastoid process). All regression parameters are significant with $P < 0.001$.

Discussion

The absolute magnitude of maximum moments measured in this experiment correspond well with those in most other studies of neck strength when compared at appropriate vertebral levels (Table 2). With the exception of the Jordan et al[13] study, other studies did not report ratios of flexion, lateral bending, or axial rotation moments relative to extension moment for individual subjects. For purposes of comparison, these values were calculated on the basis of the average reported moment in each study. Ratios of flexion-to-extension moment in the literature ranged from 0.4 to 0.7.[2,5,13,14,18] Only the values calculated from the data of Moroney et al[18] were considerably lower than the value of 0.7 calculated in the current study. The data of Choi and Vanderby[5] and Moroney et al[18] also show lower ratios of lateral bending-to-extension moment (0.5 to 0.6) than that calculated in the current study (0.7). Ratios of axial rotation-to-extension moment were 0.3 to 0.4,[2,18] similar to those calculated in the current study.

The variation in moment was quantified with the cervical level. The result confirmed a linear relation between the moment and vertical position along the cervical spine. This makes it possible to calculate moments at any location in the cervical spine, with knowledge of the moment at one location and the cervical spine geometry. In addition, a sensitivity analysis was performed to quantify the importance of errors in the point of moment resolution. From the data with moments resolved at C7–T1, moments were resolved at points displaced 1 cm in the superior–inferior, anterior–posterior, and right–left directions. A 1-cm change in point of moment resolution in the superior–inferior direction led to changes of 4% to 5% in extension, flexion, and lateral bending moments, whereas displacements in the other directions caused changes less than 1%. The anterior–posterior location of point of moment resolution does not affect the magnitude of axial rotation, indicating that the participants produced a force couple to generate axial rotation moment.

The 2 to 2.5 times greater moment-generating capacities in the men relative to the women in this study are slightly greater than the differences found in the studies of Leggett et al[15] and Moroney et al,[18] which ranged from 1.7 to 2. However, Jordan et al[13] reported ratios of male-to-female moments that were less than 1.5. The women in their study generated higher moments than in other studies. The authors suggested this may be a result of increased training and incomplete isolation of the cervical spine in their apparatus.[13]

Differences in maximum moments between men and women may arise from differences in posture, muscle size, or neural activation. In the current study, there were no significant differences in posture parameters between the men and women (Table 1), eliminating posture as a potential factor. Although there was some correlation between neck circumference and maximum moment, Conley et al[6,7] demonstrated that increases in neck strength with training are not necessarily accompanied by increases in neck muscle size. They suggested that strength increases are related to neural adaptation, and furthermore that untrained individuals may be unable to activate their cervical muscles maximally.

Differences in maximum moments between men and women do not correspond to differences in the demands made on these muscles by forces of gravitation and inertia. The mass and inertial properties are only 1.1 to 1.3 times greater in men than in women according to regression equations,[12,24] yet moments generated by men are more than two times greater than those generated by women. Therefore, it is plausible that mechanical demands on neck muscles in women are closer to their maximum moment-generating capacity. This may relate to the higher incidence of neck pain[16] and poorer recovery from whiplash injury[8] in women.

In pathologic conditions, both men and women often have diminished neck strength. This could be caused by mechanical or neural factors, or a combination of the two. For example, differences in the capacity of muscles to generate moments in three dimensions could influence mechanical equilibrium and may contribute to dysfunction. If neck muscles are operating closer to their maximum functional capacity, this could increase fatigue and decrease the ability to stabilize the cervical spine actively.

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Key Points

- The maximum neck moments generated by men were more than two times those generated by women, even when moments were adjusted for subject size. This suggests that the mechanical demands on neck muscles in women may be closer to their maximum moment-generating capacity than in men.
- The magnitude of extension, flexion, and lateral bending moments decreased linearly as the point about which moment was resolved varied from the lower cervical spine to the mastoid process.
- The ratios of maximum flexion and lateral bending moments to maximum extension moment remained consistent among subjects as the point of moment resolution varied. However, the ratio of maximum axial rotation moment to maximum extension moment was greater when moments were resolved at upper cervical levels.

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