SPINE Volume 23, Number 4, pp 412–422

Influence of Muscle Morphometry and Moment Arms on the Moment-Generating Capacity of Human Neck Muscles

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Study Design. The function of neck muscles was quantified by incorporating experimentally measured morphometric parameters into a three-dimensional biomechanical model.

Objective. To analyze how muscle morphometry and moment arms influence moment-generating capacity of human neck muscles in physiologic ranges of motion.

Summary of Background Data. Previous biomechanical analyses of the head–neck system have used simplified representations of the musculoskeletal anatomy. The force- and moment-generating properties of individual neck muscles have not been reported.

Methods. A computer graphics model was developed that incorporates detailed neck muscle morphometric data into a model of cervical musculoskeletal anatomy and intervertebral kinematics. Moment arms and force-generating capacity of neck muscles were calculated for a range of head positions.

Results. With the head in the upright neutral position, the muscles with the largest moment arms and moment-generating capacities are sternocleidomastoid in flexion and lateral bending, semispinalis capitis and splenius capitis in extension, and trapezius in axial rotation. The moment arms of certain neck muscles (*e.g.,* rectus capitis posterior major in axial rotation) change considerably in the physiologic range of motion. Most neck muscles maintain at least 80% of their peak force-generating capacity throughout the range of motion; however, the force-generating capacities of muscles with large moment arms and/or short fascicles (*e.g.,* splenius capitis) vary substantially with head posture.

Conclusions. These results quantify the contributions of individual neck muscles to moment-generating capacity and demonstrate that variations in force-generating capacity and moment arm throughout the range of motion can alter muscle moment-generating capacities.

[Key words: biomechanics, modeling, moment arms, muscle architecture, neck muscles, strength] **Spine 1998;23:412–422**

The muscles of the neck generate head movements and help maintain the stability of the cervical spine. In previous studies, investigators have examined the dynamics of head movement[9,19,20,35,50] and static neck strength in humans,[4,23,32,38] but the function of individual neck muscles has been addressed in few studies.[9,22,32,40]

The static function of a muscle may be quantified by its moment-generating capacity—the product of its moment arm and maximum isometric force. Moment arm is the distance from a muscle's line of action to the joint axis of rotation and can be calculated on the basis of a muscle's change in length with joint rotation.[3] Force-generating capacity can be derived from muscle measurements of architecture.[49] Architectural parameters include such morphometric quantities as physiologic cross-sectional area (PCSA), fascicle length, and tendon length, as well as descriptions of the arrangement of muscle fibers (*i.e.,* pennation angle). The moment generated by a muscle may be influenced by its architecture, moment arm,[15,24] and neural activation.

The complex anatomy of the head and neck musculoskeletal system poses challenges for *in vivo* measurement of neck muscle moment arms or electromyographic activity. Knowledge of muscle moment arms and force generating properties is needed to estimate the loads on spinal structures. Because muscle forces cannot be measured directly, electromyographic recordings or optimization approaches are used in conjunction with musculoskeletal models to estimate muscle forces.[22,28,32,40] The reliability of muscle force estimates depends on the accuracy of the description of the musculoskeletal anatomy. Dynamic analyses often use lumped parameter models[35,50] or combine neck muscles into functional groups based on their anatomic locations.[44] However, muscles that appear to have similar functions can have substantial differences in moment arm, force-generating

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Supported, in part, by funding from National Institute for Deafness and Communication Disorders–National Aeronautics and Space Administration center grant for vestibular research and National Science Foundation.
Acknowledgment date: February 1, 1997.
Acceptance date: June 24, 1997.
Device status category: 1.

capacity, and activation patterns. For these reasons, a biomechanical model of the cervical region that accurately represents the geometry and force-generating properties of individual muscles is needed to analyze this system.

Detailed biomechanical models based on careful observations of anatomy and kinematics have been used to examine muscle moment-generating potential and tissue loads in the lumbar musculoskeletal system.[27,28] In the cervical region, researchers have studied the *in vivo* kinematics of the cervical spine[2,10,31,36,37,45] and have quantified the skeletal anatomy,[12,33] but most measurements of neck muscle morphometry have been obtained by such indirect methods as anatomy texts or medical images.[6,9,22,32,40] Medical images can be used to estimate geometric cross-sectional areas of muscles and muscle moment arms in a single position. However, it is not possible to obtain information about muscle fascicle lengths, sarcomere lengths, physiologic cross-sectional areas, or the variation of moment arms with posture from medical images in one position. These quantities are needed to characterize a muscle's force- and moment-generating capacity accurately, but were previously undocumented for neck muscles. Kamibayashi and Richmond have recently completed a descriptive and quantitative examination of human neck musculature.[18] Their morphometric data, in conjunction with quantitative descriptions of cervical geometry and kinematics, provide a unique opportunity to examine the function of individual neck muscles.

The objective of this study was to analyze how the moment arms and morphometry affect the moment-generating capacities of individual neck muscles. A biomechanical model of the head and neck musculoskeletal system was developed that represents muscle architecture, musculoskeletal geometry and cervical spine kinematics. This model was used to evaluate the moment arms of the major neck muscles over a range of head and neck postures. Changes in muscle fascicle lengths with head posture and the related changes in force-generating capacities were calculated. Each muscle's maximum moment-generating capacity and its potential contribution to total moment at the neutral posture were quantified. Finally, the investigators examined how changes in moment arm and force-generating capacity influence moment-generating capacities over a range of head postures.

■ Methods

A graphics-based musculoskeletal model of the head and neck was developed using Software for Interactive Musculoskeletal Modeling.[7,8] The model includes skeletal geometry, muscle lines of action, muscle force-generating parameters and joint kinematics (Figure 1). These properties were used along with muscle activation to calculate muscle lengths, moment arms, forces and moment-generating capacities in a range of head and neck postures.

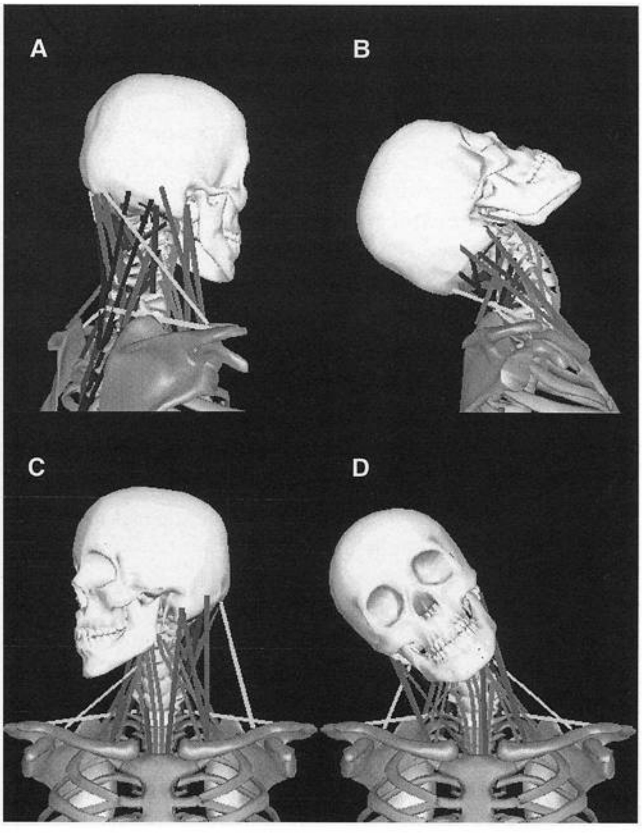

Figure 1. Graphics-based head and neck musculoskeletal model: **A**, Upright neutral posture; **B**, full extension; **C**, full right axial rotation; and **D**, full right lateral bending.

Musculoskeletal Anatomy. The skeletal geometry of the model was defined by digitized representations of the skull, mandible, vertebral column, rib cage, clavicle and scapula of a human skeleton obtained from Viewpoint Datasets (Orem, UT). Bones were scaled so that model size would match the head-to-sacrum length of a male 1.74 m in height.[13] Scaled vertebral dimensions were within one standard deviation of the average vertebral height measured in 5 of the 10 cadavers used in the associated muscle morphometry study,[17] and most were within two standard deviations of the dimensions of a larger population.[12]

Muscle attachment sites were defined visually relative to anatomic landmarks on the digitized bones, using the graphics interface. In addition to the muscle origins and insertions, via points were added to the paths of the erector spinae, longus capitis and longus colli to constrain muscles from passing through the vertebrae. Muscles with broad areas of attachment were represented by two or three subvolumes. Muscle attachment sites were chosen using published anatomic descriptions[1,18] as guidelines, enhanced by cadaver dissections and discussions with expert anatomists including collaborators at Queen's University, to ensure that the definitions of muscle segments and incorporation of muscle force-generating parameters were consistent with the experimental morphometric measurements.[18] For descriptive purposes in this paper, certain muscles were grouped together (*e.g.*, splenius capitis and cervicis, suboccipital muscles). The model includes 19 distinct muscles modeled by 25 subvolumes and placed in 9 groups (Table 1).

Muscle Force-Generating Parameters. The isometric force-generating properties of muscles were obtained by scaling a generic model of muscle.[49] This model is characterized by three dimensionless curves that are scaled by four architectural parameters that are unique to each muscle or muscle subvolume. The three curves are the active and the passive force–length curves of muscle and the force–length curve of tendon.[8] The four scaling parameters are peak isometric force, optimal fascicle length, tendon slack length and pennation angle at the neutral posture (Table 1). Peak force and optimal fascicle length scale the muscle force–length curves. Tendon slack length defines the length at which force develops in the tendon. Tendon force is calculated as muscle force multiplied by cosine of pennation angle. The active force–length curve of muscle can also be linearly scaled by neural activation, defined between 0 (passive) and 1 (maximally active).

Optimal fascicle length, pennation angle, and PCSA of most neck muscles were reported by Kamibayashi and Richmond.[18] Tendon slack length (which includes aponeuroses) was calculated as the difference between musculotendon length at the neutral head position and muscle fascicle length measured in supine cadavers. Because the model uses pennation angle as an independent parameter, PCSA was recalculated without pennation from the raw data of Kamibayashi and Richmond: $PCSA = m/(\rho \times l)$, where m = muscle mass (g), ρ = muscle density (1.06 g/cm^3)[29] and l = optimal muscle fascicle length. Peak force was calculated by multiplying PCSA by 35 N/cm^2. Kamibayashi and Richmond did not report complete architectural data for longus colli and erector spinae, because the muscles' complex attachment to vertebrae made it difficult to obtain accurate measurements. Because these muscles may contribute to the total moment-generating capacity, their force-generating parameters were estimated on the basis of available data.[6,18]

Kinematics. Each intervertebral joint between the skull and T1 has three possible rotational degrees of freedom (assuming translations are negligible). A model was developed with three total rotational degrees of freedom (flexion–extension, axial rotation, and lateral bending angles of the head relative to the trunk), in which the motion of each cervical vertebra was defined as a function of the total motion. A second model was developed with six degrees of freedom that allowed for independent motions of the upper cervical spine (skull to C2) and the lower cervical spine (C2–T1). In each model, intervertebral motions were specified as a percentage of the total motion, calculated from the values of "representative angles" of intervertebral motions reported by White and Panjabi.[43] The total angular range of motion between the head and trunk was obtained from the data of Youdas et al.[46] The centers of rotation of the intervertebral joints were defined using radiographic studies by Amevo et al.[2] Because of the scarcity of quantitative data for centers of rotation for axial rotation and lateral bending from studies *in vivo,* the centers of rotation reported for flexion and extension for all vertebral motions were used. The limitations associated with this assumption are addressed in the Discussion.

Moment Arm, Fascicle Length, and Moment-Generating Capacity Calculations. Moment arms were calculated using the partial velocity method,[8] which is equivalent to calculating the change in muscle length over an infinitesimal rotation. Because some neck muscles cross only the upper or lower cervical joints, the six degrees of freedom model was used to calculate and report moment arms separately for upper and lower cervical motion. Moment arms were averaged in muscle subvolumes or groups.

Fascicle length excursions in the physiologic range of motion were calculated from muscle attachment sites and coordinate transforms were defined by joint kinematics, using the three degrees of freedom model. Fascicle lengths in the total range of head and neck motion (Table 2) were normalized to optimal length and superimposed on a maximally active muscle force–length curve. In the model, it is assumed that active force develops in muscles in the range of 0.4–1.6 times optimal fascicle length.[49]

Moment-generating capacity was calculated by multiplying the maximum isometric force (sum of active and passive forces) generated by the muscle at a given head position by its moment arm at that position. Muscles were assumed to be maximally activated. Although moment-generating capacity can be calculated separately for individual intervertebral joints or for upper and lower cervical regions, the moment-generating capacity was reported using the three-degree-of-freedom model, because it was believed that this model was more appropriate for comparing the model predictions with human strength measurements.

Results

Moment Arms at Neutral Position

Many neck muscles have moment arms for more than one movement direction (Figure 2). Sternocleidomastoid has the largest flexion moment arm about the lower cervical joints but has an extension moment arm about the upper cervical joints (Figure 2A). In the upper cervical region, the long dorsal muscles (semispinalis capitis, splenius capitis and trapezius) have extension moment arms of greater or equal magnitude than those of the the short suboccipital muscles (rectus capitis posterior, major and minor). However, axial rotation moment arms are of similar magnitudes for suboccipital muscles and long dorsal muscles (Figure 2B). In general, moment arms for axial rotation are smaller than those for extension or lateral bending. Many muscles have their largest moment arms for lateral bending, particularly in the lower cervical region (Figure 2C).

Changes in Moment Arm With Head and Neck Posture

The moment arm of sternocleidomastoid changes dramatically during flexion–extension movements (Figure 3). For motions of the upper cervical joints, the cleidooccipital segment of sternocleidomastoid has an extension moment arm that increases in extended postures (topmost solid line in Figure 3); the other two subvolumes of sternocleidomastoid (which attach to the mastoid process) have moment arms close to zero. During flexion of

Table 1. Muscle Attachment Sites and Force-Generating Parameters Used in the Model

	Origin	Insertion	Peak Force (N)	Optimal Fascicle Length (cm)	Tendon Slack Length (cm)	Pennation Angle (°)
Sternocleidomastoid						
Sternomastoid	Sternum	Skull (m.p.)	69	10.8	5.8	15
Cleidomastoid	Clavicle	Skull (m.p.)	34	10.8	3.7	15
Cleido-occipital	Clavicle	Skull (s.n.l.)	34	10.8	7.0	15
Trapezius						
Clavotrapezius	Clavicle	Skull (occ pr)	78	8.4	12.0	30
Acromiotrapezius	Scapula (acr)	C7 (s.p.)	377	9.2	7.3	0
Suboccipital						
Rectus capitis posterior major	C2 (s.p.)	Skull (i.n.l.)	33	3.7	2.3	5
Rectus capitis posterior minor	C1 (p.t.)	Skull (i.n.l.)	18	1.9	1.7	5
Obliquus capitis superior	C1 (t.p.)	Skull (s.-i.n.l.)	37	2.5	2.0	10
Obliquus capitis inferior	C2 (s.p.)	C1 (t.p.)	45	3.8	1.6	0
Longus capitis and colli						
Longus capitis	C4 (t.p.)	Skull (bas-occ)	33	3.8	4.2	5
Longus colli–vertical	T3 (ant. v.b.)	C1 (ant v.b.)	10	8.9	8.9	5
Longus colli–superior oblique	C5 (t.p.)	C1 (ant v.b.)	10	3.6	3.6	5
Longus colli–inferior oblique	T3 (ant v.b.)	C5 (t.p.)	10	5.8	5.8	5
Splenius						
Splenius capitis–medial	C6 (s.p.)	Skull (s.n.l.)	50	9.5	2.6	0
Splenius capititis–lateral	T1 (s.p.)	Skull (m.p.)	50	9.5	8.5	0
Splenius cervicis	T4 (s.p.)	C3 (t.p.)	50	9.5	11.2	0
Semispinalis						
Semispinalis capitis–lateral	C5 (a.p.)	Skull (s.-i.n.l.)	64	6.8	4.7	5
Semispinalis capitis–medial	T1 (t.p.)	Skull (s.-i.n.l.)	64	6.8	7.8	5
Semispinalis cervicis	T1 (t.p.)	C3 (s.p.)	64	6.8	3.0	5
Scalenes						
Scalenus anterior	Rib 1	C4 (t.p.)	51	4.2	5.5	10
Scalenus medius	Rib 1	C3 (t.p.)	72	5.0	6.3	10
Scalenus posterior	Rib 2	C5 (t.p.)	55	6.2	7.4	10
Levator scapulae	Scapula (med)	C2 (t.p.)	76	11.3	2.5	0
Erector spinae						
Longissimus capitis	C6 (a.p.)	Skull (m.p.)	31	7.2	2.4	0
Longissimus cervicis	T5 (t.p.)	C4 (t.p.)	20	13.2	4.4	0
Iliocostalis cervicis	Rib 3	C5 (t.p.)	20	8.1	2.7	0

a.p. = articular process; acr. = acromion of scapula; ant v.b. = anterior vertebral body; bas-occ = basi-occiput; i.n.l. = inferior nuchal line; med = medial border scapula, between spine and superior border; m.p. = mastoid process; occ pr = external occipital protuberance; p.t. = posterior tubercle; s.-i.n.l. = between superior and inferior nuchal lines; s.p. = spinous process; s.n.l. = superior nuchal line; t.p. = transverse process.

the lower cervical joints, the flexion moment arm of sternocleidomastoid increases. Moment arms of most extensor muscles (including the suboccipital muscles) vary by 1 cm or less. However, the moment arms of some subvolumes of semispinalis capitis, trapezius, and splenius increase up to 2–3 cm from flexed to extended postures.

Moment arms in axial rotation demonstrate large variations in magnitude and even changes in direction (Figure 4). Many muscles have moment arms that vary by 2–3 cm but remain in the same direction throughout the range of motion (*e.g.,* sternocleidomastoid, splenius capitis). In other muscles, the direction of moment arm changes with axial rotation. At the neutral position, the right rectus capitis posterior major has a right rotation moment arm; its magnitude increases in left rotated postures. However, when the head is rotated to the right, the moment arm decreases in magnitude and eventually changes to a left rotation moment arm. Other muscles (*e.g.,* semispinalis capitis and longissimus capitis) exhibit similar directional changes in rotation moment arm, although they have small moment arms at the neutral position.

Changes in lateral bending moment arm with upper cervical motion are small; moment arms change less than 1 cm throughout the range of motion. During lateral bending at lower cervical joints, some muscles (sternocleidomastoid, trapezius, and the lateral portion of splenius) have increases up to 3 cm from contralateral to ipsilateral bent postures, but levator scapulae, erector spinae, and scalene moment arms remain relatively constant throughout the range of motion.

Table 2. Distribution of Cervical Range of Motion Among Upper and Lower Regions

	Flexion–Extension (°)	Axial Rotation* (°)	Lateral Bending* (°)
Upper cervical (skull–C2)	40	77	13
Lower cervical (C2–T1)	82	55	67
Total cervical range of motion	122	132	80

* Range of motion includes both sides.

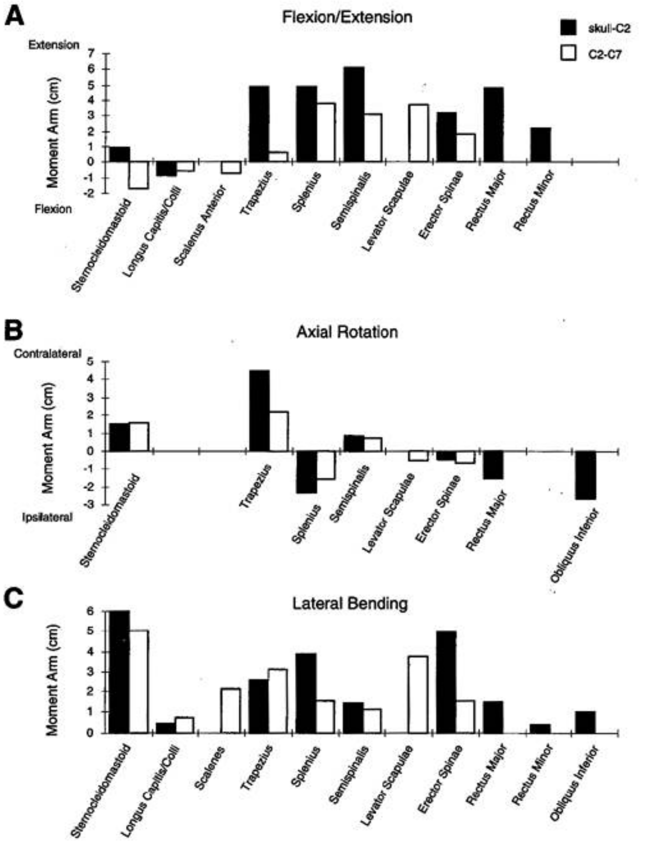

Figure 2. Neck muscle moment arms for the upper and lower cervical regions, the head and neck in the upright neutral position. Moment arms are averaged over muscle subvolumes. **A,** Flexion–extension; **B,** axial rotation; and **C,** lateral bending.

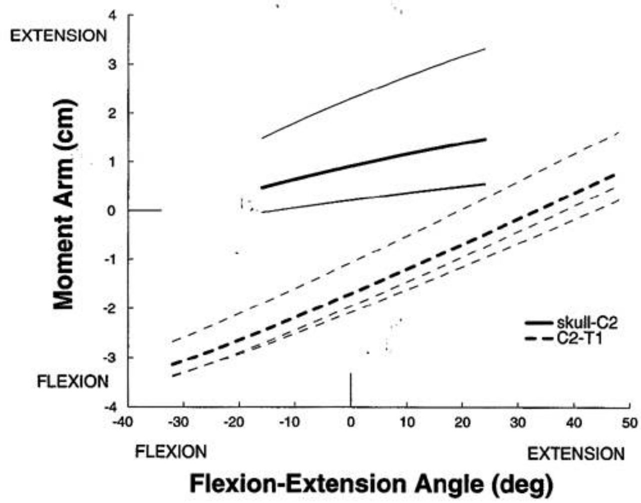

Figure 3. Sternocleidomastoid flexion–extension moment arms throughout the range of motion (individual subvolumes [light lines] and average [dark lines]). Solid line indicates moment arm for the upper cervical region; dashed line indicates lower cervical region. In both regions, the cleidooccipital subvolume has a larger extension (or smaller flexion) moment arm than the sternomastoid and cleidomastoid subvolumes. The moment arms for sternomastoid and cleidomastoid are indistinguishable in the upper cervical region.

Changes in Fascicle Length With Head Posture

In the neutral posture, measured muscle fascicle lengths were within 15% of their optimal length.[18] Examining all three directions of motion, more than half of the neck muscles experience fascicle length changes of less than 30% of their optimal length; this corresponds to maintaining at least 80% of peak force throughout the range of motion. However, many extensor muscles undergo larger length changes in the flexion–extension range of motion; splenius capitis, semispinalis capitis, semispinalis cervicis, rectus capitis posterior major, and rectus capitis posterior minor all experience fascicle length changes of more than 70% of optimal length. During axial rotation, only the clavicular portion of trapezius, rectus capitis posterior major, and obliquus capitis inferior demonstrate length changes of more than 50% of optimal fascicle length; and sternocleidomastoid, scalenus anterior and medius, and the clavicular portion of trapezius undergo more than 50% change during lateral bending. The changes in active force-generating capacity associated with some of the larger fascicle length variations are demonstrated in Figure 5.

The calculated operating ranges of neck muscle fascicles can vary considerably among muscles and even with different movement directions for the same muscle. For example, the fascicles of sternocleidomastoid are calculated to act on the plateau region during flexion and extension, enter the descending limb of the force–length curve during axial rotation, and use much more of the

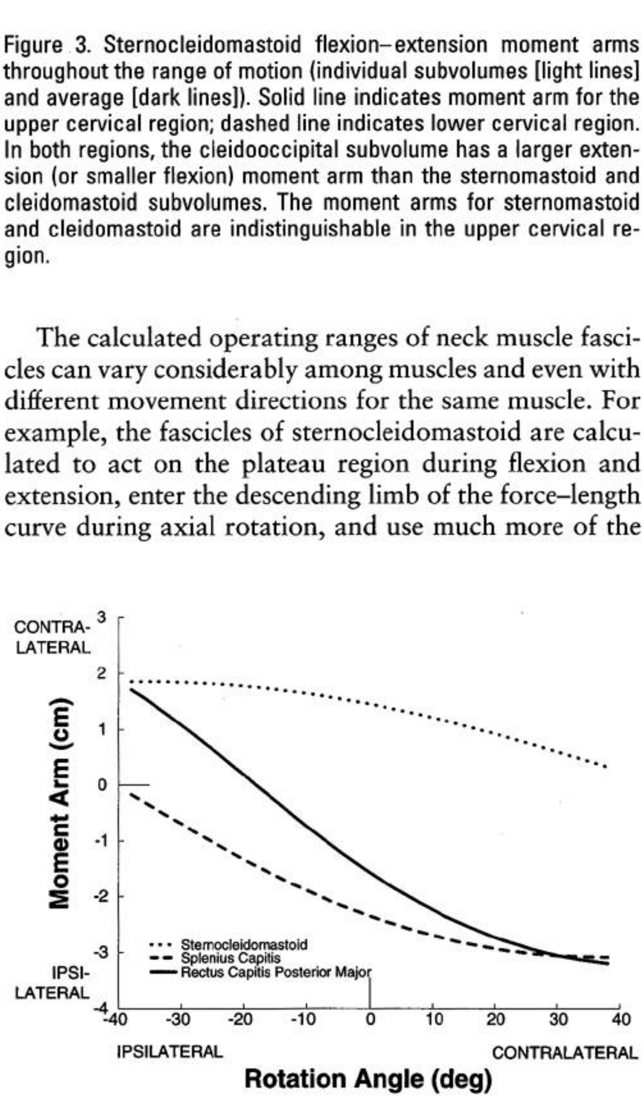

Figure 4. Axial rotation moment arms for the upper cervical region, plotted throughout the range of upper cervical rotation. Dotted line = sternocleidomastoid (average of three subvolumes); dashed line = splenius capitis (average of two subvolumes); solid line = rectus capitis posterior major.

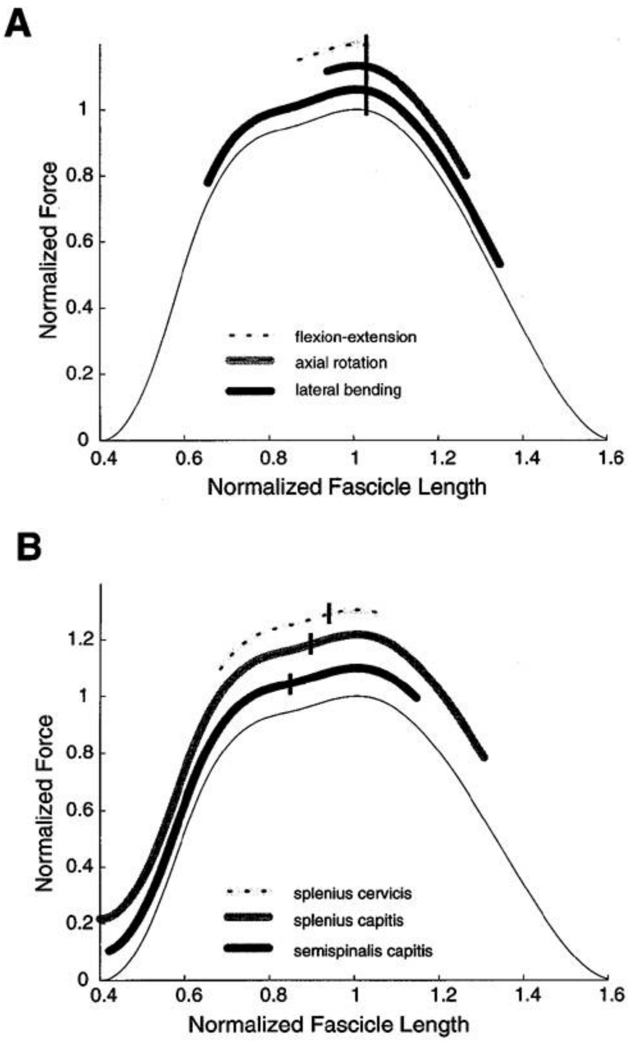

Figure 5. Fascicle length excursions superimposed on normalized muscle active force–length curves. Range of motion is 50° in flexion, 72° in extension, 132° in axial rotation (±66°), and 80° in lateral bending (±40°). Vertical lines indicate fascicle length at neutral head position. **A,** Sternocleidomastoid (cleidooccipital fascicles) operating ranges during flexion–extension (dotted line), axial rotation (dashed line), and lateral bending (dot–dash line). **B,** Splenius cervicis (dotted line), splenius capitis (dashed line), and semispinalis capitis (dot–dash line) operating ranges during flexion–extension.

force–length curve (50–70%) during lateral bending (Figure 5A). Certain muscles that are considered to have similar functions may experience different fascicle length excursions in the same range of motion. For instance, splenius cervicis operates on the plateau region during the entire 122° range of flexion–extension motion (Figure 5B), whereas splenius capitis uses a much larger portion of the force–length curve. Although their fascicle lengths are equal, the larger moment arm of splenius capitis results in much larger fascicle length changes. Semispinalis capitis has a smaller moment arm than does splenius capitis but operates in a large portion of its force–length curve because its fascicle lengths are shorter. In general, muscles with larger ratios of optimal fascicle length to moment arm for a particular degree of freedom experience smaller changes in fascicle length in the same range of motion.

Isometric Moment-Generating Capacity at Neutral Position

With all muscles maximally activated, the model estimates that most of the extension moment-generating capacity of 34 Nm comes from semispinalis (37%) and splenius (30%). Levator scapulae, trapezius, erector spinae, and suboccipital muscles also potentially contribute 5–10% each to extension moment-generating capacity (Figure 6A). Estimated flexion moment-generating capacity of 4 Nm is dominated by sternocleidomastoid (69%), with additional contributions from longus capitis and colli (17% total) and scalenus anterior (14%) (Figure 6B). The predicted moment-generating capacity for axial rotation (11 Nm total) is greatest for trapezius (32%), followed by 10–20% each from splenius, sternocleidomastoid, semispinalis, and suboccipital muscles (Figure 6C). The total moment-generating capacity for

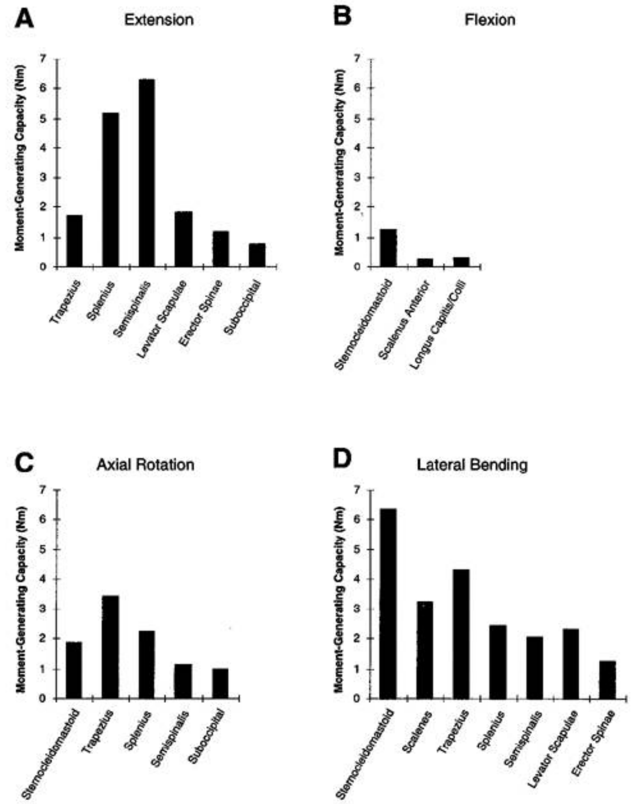

Figure 6. Moment-generating capacity of neck muscles at the neutral position. **A,** Extension (total = 34 Nm); **B,** flexion (total = 4 Nm); **C,** axial rotation (total = 11 Nm); and **D,** lateral bending (total = 23 Nm).

lateral bending (23 Nm) is greatest for sternocleidomastoid (28%) and trapezius (19%), with the scaleni, splenius, levator scapulae, semispinalis, and erector spinae estimated to contribute 5–15% each (Figure 6D).

Changes in Isometric Moment-Generating Capacity With Head and Neck Posture

The total moment-generating capacity of the neck extensors decreases in both flexed and extended postures (Table 3). In flexed postures, extensor force-generating capacities remain approximately constant, but extension moment arms tend to decrease. However, with more than 20° of extension, the estimated force-generating capacity of some extensors can drop appreciably (most notably semispinalis and splenius, which have the largest extension moment-generating capacity in neutral position).

The model estimates that total flexion moment-generating capacity almost doubles in postures of 40–50° flexion, because of the increase in sternocleidomastoid flexion moment arm. In extremely extended postures, the total flexion moment-generating capacity can potentially decrease to less than 25% of the value at neutral, because of decrease in flexion moment arms of both sternocleidomastoid and scalenus anterior.

When the head is rotated to the right, the capacity to generate right axial rotation moment can decrease by more than 50%, whereas the capacity to generate moment to the left increases by up to 50%. This occurs primarily because of decreases in the moment arms of muscles that produce right rotation (right splenius and rectus capitis posterior major; left sternocleidomastoid, trapezius and semispinalis); conversely, the moment arms of muscles that produce left axial rotation increase in right rotated postures (with the exception of trapezius). For most muscles, force-generating capacity remains constant throughout the range of axial rotation; however the force-generating capacities of left trapezius and right rectus capitis posterior major decrease with right rotation.

Estimated lateral bending moment-generating capacity decreases by up to 30% in contralateral postures, but varies less than 5% in ipsilateral postures. Decreases in moment-generating capacity in contralaterally bent postures occur mainly because of decreases in moment arm, with some decrease in force-generating capacity. In ipsilaterally bent postures, total moment-generating capacity changes little, because increases in moment arms generally balance the decreases in force-generating capacities.

Discussion

Computer models are particularly useful in analyzing the biomechanics of the human head and neck musculoskeletal system, because limited data can be obtained directly from studies *in vivo*. Several assumptions have been made in the development of the model presented here and should be understood to interpret the results accurately.

In computation of moment-generating capacity, it was assumed that all muscles that could contribute to total moment-generating capacity were maximally activated. *In vivo,* all muscles with appropriate moment-generating capacity may not be simultaneously, or maximally, activated. In addition, activity in antagonist muscles may decrease the net moment. Although the actual moment generated by each muscle depends on its activation, in this study the effects of muscle moment arms and morphometry on moment-generating capacity were isolated and the upper bounds for the static moment-generating capacities of neck muscles were defined.

In the current model, muscles were constrained to wrap over vertebrae when appropriate, but the paths of the muscles were not constrained to wrap over other muscles. In other models, muscle paths have been represented as arcs[28] or as wrapping over simple geometric shapes,[42] but no general algorithm has been developed to represent the three-dimensional interaction of muscle surfaces. If it were possible to include the constraints imposed by other muscles in the current model, it could affect the moment arms, particularly for long, superficial muscles near the ends of the ranges of motion.

The skeletal geometry of the model described here is based on a male approximately 1.74 m in height,[13] whereas the morphometric parameters are averages from 10 cadavers (7 men and 3 women), ranging from a petite female to a large male.[18] Despite the interindividual variations, most musculotendon lengths calculated in the model were within one standard deviation of those measured in the cadavers. The results of this study are not meant to be directly extended to people of all sizes; rather, they serve to elucidate the relative values of individual muscle moment arms and force- and moment-generating capacities.

A sensitivity analysis was performed to understand the influence of variability in modeling parameters. Varying both optimal fascicle length and fascicle length at neutral by one standard deviation or setting pennation angle to zero resulted in changes of less than 5% in total moment-generating capacity. Variation of PCSA by one standard deviation, however, caused larger changes in moment-generating capacity (25–32%). In addition to variability of PCSA, the peak isometric force of muscles is affected by the scaling factor of specific tension. Values for specific tension in the literature range from 23 N/cm^2 when force was directly measured in cat hind limb[41] to 35–55 N/cm^2 used in modeling studies.[28] Thirty-five 35 N/cm^2 was chosen primarily to compensate for the decreased muscle size in elderly cadavers.[47,48] Clearly, the choice of specific tension value will affect the total moment-generating capacity predicted by the model, but it

Table 3. Neck Muscle Moment-Generating Capacities Predicted With the Model in Various Postures

	Flexion–Extension Moment (Nm)*			Axial Rotation Moment (Nm)†			Lateral Bending Moment (Nm)‡		
	Flexion (−30°)	Neutral	Extension (30°)	Right Rotated (−30°)	Neutral	Left Rotated (30°)	Left Bending (−30°)	Neutral	Right Bending (30°)
Sternocleidomastoid									
Right	−2.5	−1.2	−0.4	2.1	1.9	0.9	4.1	6.3	7.1
Left	−2.5	−1.2	−0.4	−0.9	−1.9	−2.1	−7.1	−6.3	−4.1
Trapezius									
Right	1.0	1.7	2.1	2.7	3.4	2.8	3.1	4.3	3.8
Left	1.0	1.7	2.1	−2.8	−3.4	−2.7	−3.8	−4.3	−3.1
Splenius									
Right	4.6	5.2	3.9	−0.9	−2.2	−2.9	1.5	2.4	2.9
Left	4.6	5.2	3.9	2.9	2.2	0.9	−2.9	−2.4	−1.5
Semispinalis									
Right	5.5	6.3	2.9	2.2	1.1	−0.2	1.5	2.1	2.4
Left	5.5	6.3	2.9	0.2	−1.1	−2.2	−2.4	−2.1	−1.5
	Flexion			Right Axial Rotation			Right Lateral Bending		
Total§ (all muscles)	−6.4	−3.6	−1.8	−6.0	−10.6	−13.4	16.8	22.6	23.4
	Extension			Left Axial Rotation			Left Lateral Bending		
Total§ (all muscles)	29.3	34.1	26.5	13.4	10.6	6.0	−23.4	−22.6	−16.8

* Extension moment is positive.
† Left axial rotation moment is positive.
‡ Right lateral bending moment is positive.
§ Total moments include contributions from additional muscles.

will not affect the relative contributions of different muscles or the variations that occur with posture.

The complexity of cervical spine kinematics present a significant modeling challenge. In the literature, there is a large range of values for centers of rotation and ranges of motion. The current investigators noted that altering the centers of rotation at the intervertebral joints by one standard deviation[2] in the sagittal plane affected flexion moment-generating capacity the most (up to 20%), extension less (up to 5%) and had very little effect (less than 1%) on axial rotation or lateral bending moment-generating capacity. There is little quantitative data on the location *in vivo* of center of rotation for lateral bending or axial rotation. The lateral offset (distance from midsagittal plane) of the centers of rotation for axial rotation and lateral bending were estimated on the basis of the results of a study *in vitro* of helical axis of motion,[30] and the resulting decreases in total moment-generating capacity were 2–5% in axial rotation and lateral bending.

Coupled motions of axial rotation and lateral bending are also key features in cervical spine kinematics. Specifically, axial rotation is accompanied by lateral bending to the same side in the lower cervical region and by compensatory bending to the opposite side in the upper cervical region; a similar relation with axial rotation occurs when lateral bending is the primary motion.[16,25,31,34] However, there is large variability in the coupling ratios presented in the literature, and no one data set reports the coupled motions associated with both axial rotation and lateral bending for upper and lower cervical levels. In addition, definition of kinematics used in the current study precluded using distinct coupling ratios at each intervertebral joint. For these reasons, coupled motions were not explicitly included in the model, but can be incorporated in the future. A preliminary analysis using different coupling ratios at upper and lower cervical regions (averages from the literature)[16,25,31,34] showed that coupled motions altered total axial rotation and lateral bending moments by less than 5–10% throughout most of the range of motion. Axial rotation moment-generating capacity in the upper cervical region was more affected by coupled motions at extremely rotated postures.

The results of this study emphasize the need to account for the variation of moment arms with head and neck posture. The results indicate that characterizing a muscle's function by identifying moment arm at the neutral position (*e.g.*, with computed tomographic scan or magnetic resonance study) may not accurately reflect potential moment-generating capacity in other postures. These changes in neck muscle moment arms may be important in understanding muscle roles in head stabilization. For example, rectus capitis posterior major has an axial rotation moment arm appropriate to restoring the head to neutral posture from most rotated head positions (Figure 4). This is particularly relevant because most axial rotation occurs in the upper cervical region, between C1 and C2. In contrast, the change in sternocleidomastoid flexion moment arm indicates a destabilizing effect, because it potentially increases the muscle's flexion moment-generating capacity in flexed postures (Figure 3).

In some muscles, large variation in fascicle lengths were observed with changes in posture. The force–length effect presents a challenge to the nervous system, because muscles with large moment-generating capacity at neutral posture may not be able to maintain the same force-generating capacity throughout the range of motion. These biomechanical factors may influence changes in muscle activation with posture. However, the changes in force-generating capacity estimated in this study represent extreme values. The force–length relation of muscle fascicles may have a broader plateau region than that of sarcomeres.[14] In addition, the extreme postures analyzed in this study may not occur during natural movements. A similar analysis of cats tracking a drinking spout with 30° flexion–extension movements showed that fascicle lengths of most neck muscles remained on the plateau region.[21]

Extension and axial rotation moment-generating capacities predicted by the model corresponded with experimental measurements of human neck strength at the neutral position. The extension moment-generating capacity predicted by the model (34 Nm) is within the range reported in results of many experimental studies (24–36 Nm).[4,22,23,32,38] Some studies measuring forces at the occiput and resolving moments at C7–T1 report higher extension moment (53–60 Nm).[26,39] Axial rotation moment-generating capacity of 11 Nm is close to that reported in the literature (9–11 Nm).[4,32] Lateral bending moment-generating capacity (23 Nm) is larger than the value reported in the literature (13 Nm).[32]

The flexion moment-generating capacity predicted by the model (4 Nm) is considerably lower than the values reported in the literature (which range from 10 Nm to 19 Nm).[4,22,32] The low flexion moment-generating capacity of the model may arise from one of several modeling assumptions. For example, centers of rotation may be different for flexion and extension. Although this difference has not been documented, it alone is unlikely to account for the low flexion moment-generating capacity; varying centers of rotation by two standard deviations from the values reported in the literature[2] results in a 34% increase in flexion moment-generating capacity in neutral position (to 4.8 Nm). Muscles that are not included in the model may generate flexion moment. For instance, the infrahyoid muscles have large moment arms for neck flexion; however, there is no conclusive evidence that these muscles contribute to neck flexion moment.[5,11]

The results of this investigation emphasize the importance of detailed measurements of muscle architecture in estimating moment-generating capacity accurately. As illustrated by Kamibayashi and Richmond, many neck muscles have unique architectural features that are not apparent from superficial dissection or medical imaging.[18] These features can influence the force- and moment-generating properties of the muscles. For example, modeling sternocleidomastoid without the deep cleidomastoid segment (but with the same PCSA) decreases its predicted flexion moment-generating capacity by 36% in the neutral position. Overlooking deep, pennate fascicles can also decrease a muscle's calculated PCSA (Kamibayashi and Richmond, Table 3).[18] Using PCSA and optimal fascicle length parameters derived without the values from deeper fascicles decreased predictions of force- and moment-generating capacity by 15% in obliquus capitis superior, 30–40% in steocleidomastoid, and up to 60% in longus capitis.

This reports provides the first description of the moment-generating capacity of individual neck muscles. Using experimental muscle morphometric data and a graphics-based computer model of the head and neck musculoskeletal system, muscle moment arms and force-generating capacity have been quantified and their influences on moment-generating capacity examined across a range of head postures. These data are needed to understand the function of these muscles, to estimate tissue loads in the cervical spine, and to analyze control of head and neck movements.

Acknowledgments

The authors thank Drs. Lynne Kamibayashi and Frances Richmond for their work in measuring neck muscle morphometric parameters and for insightful discussions regarding incorporating these parameters into a musculoskeletal model.

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