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Measurement of Human Neck Muscle Volume Geometry and Physiologic Cross Sectional Area in 5th, 50th, and 95th Percentile Subjects Using Cadaveric Dissection and MRI

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INTRODUCTION:

The ability of computational models to describe head and neck dynamics depends upon the accuracy of the mechanical and geometric representation of each of the constituents. While the structure of the ligamentous cervical spine has been well-studied (Nissan and Gilad, 1984), characterization of the neck's muscular geometry, and hence its structural properties, are largely absent. As a result, many neck models have neglected the effects of the musculature on head-neck dynamics. Cervical spine studies that do cite muscle geometric data include the works of Weber (1851), Berry (1911), Eycleshymer and Schoemaker (1911), and Reber (1978). The Berry data, however, contains only slices from one embalmed cadaver (25 yr. old Aborigines donor) taken every 2 cm from the base of the skull to C3, and longitudinal sections obtained from a different donor. Eycleshymer and Schoemaker's data includes composite artist's drawings of 50 "Negro" donors presented at approximately 4/5 scale. Additionally, the authors note that few of the donors appeared average, and most were obese or severely emaciated. Reber (1978) defined muscle cross-sectional area as the average of the tendonous origin and insertion of the muscle as shown on a set of "human bones" from an unknown donor.

Recent efforts have utilized finite element methods to approximate the complex geometry of spinal structures (Liu, 1986, Saito et al., 1989, Kleinberger, 1993, Dauvilliers et al., 1994, Yoganandan et al., 1995, Camacho et al., 1997), and provide insight into local stresses and strains. However, these models have not incorporated the effects of the musculature. A lack of precise volumetric dimensional data of the cervical musculature has been noted as the primary difficulty in modeling the human spine precisely (Dietrich et al., 1991). Furthermore, the absence of quantitative data on muscle behavior has resulted in the need to estimate these properties (Deng and Goldsmith, 1987).

Unfortunately, analysis of muscle actuated systems has been shown to be profoundly sensitive to changes in muscle geometry. Hertzog (1992) illustrated that a change of the physiologic cross-sectional area (PCSA) of one of two synergistic muscles from 27 cm² to 63 cm² produced increases in muscle force between 134% and 446% depending on the model. Clearly, the lack of data characterizing skeletal muscle properties and geometry has remained a primary limitation in the assignment of muscle model constants and the assessment of the effects of cervical musculature on the cervical spine.

Physiologic cross-sectional area is a common geometric representation of muscles (Lieber, 1992) and is commonly used in computational models to describe muscle architecture (Li et al., 1997). Human cadaveric studies have attempted to estimate live human PCSA by the weighing of tissue (Kambayashi and Richmond, 1997). These studies, however, have not accounted for losses in muscle volume due to age, peri-mortem atrophy, and post-mortem desiccation. There are also no known quantitative relationships between PCSA measured in cadaveric specimens and the PCSA of human subjects. Further, cadaveric studies have been unable to characterize the differences in the volume geometry that are present between specific segments of the population owing to the poor quality and limited availability of cadaver tissue. Yet, cross-sectional areas of neck musculature may vary significantly between distinct anthropometric groups (i.e. 50thile male, 95thile male and 5thile female).

In contrast, magnetic resonance imaging (MRI) has been used successfully to measure muscle volumes without the confounding effects of peri-mortem and post-mortem changes. Tuang et al. (1993) reported PCSA in tenths of cm² from serial MRI sections in lumbar spine imaging studies, and Reid et al. (1987) characterized lumbar musculature in young athletic subjects using MRI. Santiguada and McGill (1995) performed a full three-dimensional reconstruction of the psoas muscle with this technique. MRI, however, is not able to accurately measure fiber length or sarcomere length and pennation angle can only be estimated using diffusion tensor technology, which is not readily available. Accordingly, the purpose of this study is to estimate PCSA of distinct anthropometric groups by the use of both cadaveric dissection and MRI, and provide quantitative data on cervical spinal musculature suitable for incorporation into structural and finite element models of cervical dynamics.

MATERIALS AND METHODS:

Three human cadavers (ages 71, 83 and 79 years), embalmed between 24-48 hrs. post-mortem, were obtained and dissected at the T4-T5 level. Tissue biopsies were obtained prior to dissection to ensure adequate preservation of the muscle cellular microstructural architecture. Specimens were mounted in an upright anatomic position by casting the lower thoracic vertebrae into an aluminum cup with reinforced polyester resin, and mounting the cast in an aluminum frame. The rostral end of the specimen was then mounted to the space-frame using a halo fixture. The halo afforded anteroposterior, rostral-caudal, and sagittal plane angular motion to allow mounting of the specimen with the Frankfort plane horizontal, and T1 at 25 degrees from horizontal. Each of the cervical muscles originating above T2 that could be adequately dissected was included in this study. Muscles that inserted below T2 were dissected sharply at T2 and analyzed by assuming that the

muscle insertion was at T2. Muscles that had multiple attachments or distinct subvolumes were divided and analyzed separately.

Dissection of the cadaver was carried out by exposing the origin and insertion of each muscle. A Microscribe 3-D Digitizer (Immersion Corporation, San Jose, CA) with Hyperspace Modeler software (Mira Imaging, Salt Lake City, UT) was used to acquire the three-dimensional coordinates of the origin and insertion. A line of action was traced along the length of the muscle and digitized. Pennation angle, defined as the angle of orientation of the fascicles relative to the line of action of the muscle was measured with a protractor. Additionally, as many as 25 evenly spaced sites on each muscle were designated for sarcomere length measurement and their locations digitally recorded. Each muscle was then dissected and weighed. Sites designated for sarcomere measurement were isolated by dissection and stored in an EDTA rigor solution. Muscle lengths were calculated by using the length of a cotton suture placed at the origin and insertion of the muscle. Fiber length was obtained by first submerging the muscles in a 20% H₂SO₄ solution for four days to disrupt the connective tissue. Full muscle fibers were then dissected from one to four representative sites depending on the muscle geometry and average fiber length measured.

Sarcomere lengths were determined using one of two methods. Single fibers were dissected, mounted on slides using an EDTA solution, and measured using an inverted microscope system with phase-contrast objective (Olympus Optical Co., Tokyo, Japan) at a magnification of 40X. Sarcomere lengths were also measured by directing a 10mW helium-neon laser (Uniphase, Manteca, CA) through isolated muscle fiber bundles containing less than 10 fibers. The distance to the first diffraction band was measured and transformed to sarcomere length using a nonlinear scale (Fleeter et al., 1985).

Following removal of all muscles from the specimen, the vertebral column was defatted and cleaned of remaining tissue, and skeletal landmarks were digitized. Each vertebral body (C1-T2) was digitized along its midsagittal superior and inferior borders in addition to the line characterizing the superior and inferior edges of the transverse and spinous processes. The Frankfort plane was also digitized, and the distance between the glabella and opisthocranium measured using calipers.

To obtain muscle volume geometry, three human subjects, a 95thile male, 50thile male, and 5thile female were studied using MRI. Scans were performed on a 2.0 T GE Signa magnet using a 3D-gradient echo technique and a TR:TE ratio of 35:9. Two sets of scans with 256 x 256 voxels in the horizontal plane were obtained for each subject. The first scan had a horizontal plane field-of-view of 20 cm x 20 cm that enclosed the complete neck but truncated the trapezius muscular insertion. The second scan had a horizontal plane field-of-view of 40 cm x 40 cm that included the trapezius insertion. Each scan included the skull base superior to the most rostral muscular origin through to the T4 in 2 mm slices.

Images were downloaded to an IBM PC (Dell Computers, Austin, Texas) and the individual muscle borders digitized using ImageTool (University of Texas Health Science Center, San Antonio, TX). A C++ program was written to calculate the area of the digitized contours on each slice. The volume of each muscle was then calculated by multiplying each corresponding contour area by the slice thickness, and summing all of the layers comprising a given muscle. Individual muscles, which

could not be isolated by MRI, were grouped and digitized together. They were assigned individual volumes by multiplying the group volume by the mass ratios obtained from cadaver dissection of the same groups.

RESULTS:

Twenty-four unique muscle groups could be dissected and measured from three cadavers. Cervical muscles that were not dissected consisted primarily of muscles located between adjacent vertebrae. These include the rotatores cervicis longus, rotatores cervicis brevis, multifidous, longus colli, rectus capitis anterior, rectus capitis lateralis, and interspinalis cervicis. Muscles that were dissected are summarized in Table 1 with the numbers of specimens collected to date in parentheses. Mean fiber length was $70.1 \pm 12.1\%$ of the total muscle-tendon length, with iliocostalis cervicis, longissimus cervicis and longus capitis having particularly large tendonous regions. Additionally, each of the muscle groups studied, excluding the trapezius, which has a complex architecture, were found to be nearly fusiform with pennation angles of less than two degrees. Because of its complex architecture, the trapezius muscle was divided into two partitions. Fibers running horizontally from a spinal origin to the scapular insertion were assigned to one partition, while fibers originating from the base of the skull were assigned to a second partition. Average sarcomere length was $2.61 \pm 0.271 \mu\text{m}$.

Table 1: Cadaver Muscles Dissected

Iliocostalis (2)	Posterior rectus capitis minor (2)	Semispinalis capitis (5)
Inferior oblique capitis (5)	Rhomboideus major (2)	Semispinalis cervicis (6)
Superior oblique capitis (3)	Rhomboideus minor (3)	Sternocleidomastoid (4)
Levator scapulae (5)	Anterior scalene (6)	Omohyoid (1)
Longissimus capitis (3)	Middle scalene (5)	Sternohyoid (1)
Longissimus cervicis (3)	Posterior scalene (5)	Sternothyroid (1)
Longus capitis (4)	Splenius capitis (6)	Thyrohyoid (1)
Posterior rectus capitis major (5)	Splenius cervicis (4)	

Using the MRI scanning technique, muscle had a high signal intensity, while the interposed fascia had a low signal intensity (Figure 1). As a result of this contrast, a total of 21 muscle groups could be identified on MRI including all of the dissected muscle groups. Muscles that could not be individually partitioned on MRI included splenius capitis/cervicis, longissimus capitis/cervicis, longus capitis/anterior scalene, middle scalene/posterior scalene and the hyoid group (sternohyoid, sternothyroid, omohyoid, thyrohyoid). To date, a total of eight scans have been completed.

Human subject volumes derived from an MRI of a 50%ile male were found to be $66 \pm 0.47\%$ greater than the average volumes measured from the three cadavers. Additionally, differences between anthropometric groups were also large. Specifically, muscle volumes for a 95%ile male were $62 \pm 45\%$ greater than those of the 50%ile male, and a 5%ile female was $83 \pm 32\%$ smaller than the 50%ile male.

Interestingly, the hyoid muscle group, often neglected in anatomic and biomechanical studies, was found to have the potential to act as a significant neck flexor. Data from a 50%ile male showed that

the hyoids possess a volume of approximately 23 cm^3 or 27% of the combined volume (84 cm^3) of the other known neck flexors (sternocleidomastoid, longus capitis, longus colli, anterior scalene). The hyoids, which insert on the sternum and clavicle and originate on the hyoid bone, also possess a larger moment arm ($\sim 4\text{cm}$) when compared to the neck flexors located adjacent to the vertebral column whose moment arms are less than 1 cm.

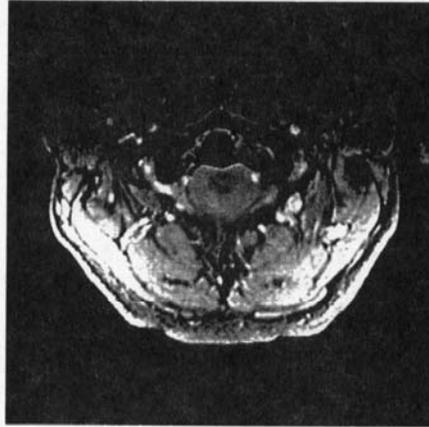


Figure 1: A magnetic resonance image of a 20x20 cm field of view showing high signal intensity muscle bounded by low signal intensity fascia which allowed for easy identification of muscle boundaries.

DISCUSSION:

The lack of data characterizing cervical musculature geometry has been a primary limitation in the ability of computational models to describe head-neck dynamics. Existing data have either been qualitative or have relied on cadaveric measurements to estimate muscle PCSA. Efforts to estimate PCSA by the weighing of cadaveric tissue cannot account for losses in muscle volume due to age, peri-mortem atrophy and post-mortem desiccation. The data presented here show that these effects cause errors in PCSA which are both large and highly variable. Additionally, cadaveric study is unable to determine the changes in volume geometry that occur between distinct anthropometric groups within the population owing to the poor quality and limited availability of cadaver tissue. These preliminary results indicate that these volumetric changes may be as large as 400% when comparing a 5th percentile female to a 95th percentile male. In the same light, sarcomere length data, which influences the isometric tetanic stress generated in a muscle (Lieber, 1992) has been largely unavailable in the literature. These preliminary results show a range of sarcomere lengths for 2.3 to 3.3 μm which is in agreement with the results recently reported by Kambayashi and Richmond (1997).

It has long been recognized that head flexor muscles are weaker than head extensor muscles (Mertz and Patrick, 1967, 1971). That said, few muscle groups have been identified which have both adequate mass and moment arms to flex the entire cervical spine. Indeed, recent muscle optimization studies have failed to agree with measured quasi-static moment (Li et al., 1997). Our preliminary data suggest that the historically neglected hyoid muscles may be the basis for this discrepancy, as they appear to have both the mass and moment arm necessary to serve as neck flexors. Further work to generate meaningful statistical populations and to apply these data to a comprehensive neck model are required to better study this hypothesis.

CONCLUSIONS:

This preliminary report demonstrates that MRI has adequate resolution to identify most of the cervical muscle groups and to provide quantitative muscle volume data from specific anthropometric groups of the population. Using MRI, the average error in PCSA determined from cadaver dissection was found to be 66% for the 5th percentile female. Further, variations in muscle volume between the 50th male and the 95th male and 5th female were found to be +62% and -83%, respectively. Based on this geometric study alone, the hyoid muscle group appears to have the potential to act as a significant neck flexor.

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DISCUSSION

PAPER: **Measurement of Human Neck Muscle Volume Geometry, and Physiologic Cross Sectional Area in 5th, 50th, and 95th Percentile Subjects Using Cadaveric Dissection and MRI**

PRESENTER: Kurt Knaub, Duke University

QUESTION: Guy Nusholtz, Chrysler Corporation

Why do you think there was a difference between the volume in the MRI and the cadaver subjects?

ANSWER: Well, we've done roughly three or four cadaver dissections now, and most of them were elderly. Many of them spent months in the hospital beforehand and the muscles were atrophied. The mean age was eighty, and you can't really sit down and do a full dissection in a single day and accurately record the properties. A lot of times, just desiccation of the muscles, even though we tried to keep them as wet as possible especially for weighing. You are just pretty much unable to do it. So, I think for the most part, those are the reasons why the muscle volumes go down.

Q: Alright, thank you.

Q: Michael Kleinberger, NHTSA

I'd like to follow up on that a little bit. Are you stating here that the differences you see are not necessarily part of the postmortem or embalming process, but are due to the subjects being elderly and hospital bound rather than normal, young, healthy subjects?

A: Yes. I'm not sure that the embalming process or post mortem has a significant effect on it. I think the only real difference you're seeing is in desiccation. Muscles, even if you re-wet them, have significantly less volume. So, yes, I would say prior to death is where you are losing most of the volume. We are also unable to specifically target populations which have healthy muscles, and exercise regularly.

Q: It might be interesting to document this if you can get a fresh cadaver specimen and then do pre and post embalming measurements, or over some time period. That might be interesting.

Q: (From the floor)

Can I make a comment there? There is a big difference with somebody that is alive because you have tissue profusion, which is not present in the cadavers and that can make a large difference.

A: Right, the blood in the muscle makes a big difference.

Q: Dave Meany, University of Pennsylvania

Just a question I guess related to that. It seems with measuring the microstructure; you at least have some sense down the road of using it that some point, whether it is looking at more subtle types of injuries, for example, to the muscle group. My question is when you see these differences in cadaveric versus MR at the more macro level, that is, basically volume geometry changes, how do you think it is going to scale down to the micro level. Do you think you could make a transition? It is more just asking for thoughts. There is no right answer.

A: I'm not sure. As far as scaling from macro to micro, I'm really not sure.

Q: Dr. Myers

It is an interesting question. It will be fun once we have more of this data to be able to ask questions like what are the exposures of the muscles once we have reasonable representations under the kinds of kinematics that we know we can see. One comment to an earlier question was the influence of embalming on muscle volume. Agents like formalin, when you are doing histologic preparations, produce distortions of about 1%, so the act of embalming is not causing the volume error. The errors are desiccation and premortem changes, so it is not actually embalming that is a problem.

Q: OK. Thank you, Kirk.