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Sex-specific prediction of neck muscle volumes

Liying Zheng [a], Gunter Siegmund [b,c], Gulsum Ozyigit [a,d], Anita Vasavada [a,*]

[a] Washington State University, Pullman, WA 99164-6520, USA
[b] MEA Forensic Engineers & Scientists, Richmond, BC, Canada
[c] University of British Columbia, Vancouver, BC, Canada
[d] Uludag University, Bursa, Turkey

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ABSTRACT

Biomechanical analyses of the head and neck system require knowledge of neck muscle forces, which are often estimated from neck muscle volumes. Here we use magnetic resonance images (MRIs) of 17 subjects (6 females, 11 males) to develop a method to predict the volumes of 16 neck muscles by first predicting the total neck muscle volume (TMV) from subject sex and anthropometry, and then predicting individual neck muscle volumes using fixed volume proportions for each neck muscle. We hypothesized that the regression equations for total muscle volume as well as individual muscle volume proportions would be sex specific. We found that females have 59% lower TMV compared to males (females: 510 ± 43 cm^3, males: 814 ± 64 cm^3; $p < 0.0001$) and that TMV (in cm^3) was best predicted by a regression equation that included sex (male = 0, female = 1) and neck circumference (NC, in cm): TMV = 269 + 13.7NC − 233Sex (adjusted $R^2 = 0.868$; $p < 0.01$). Individual muscle volume proportions were not sex specific for most neck muscles, although small sex differences existed for three neck muscles (obliqus capitis inferior, longus capitis, and sternocleidomastoid). When predicting individual muscle volumes in subjects not used to develop the model, coefficients of concordance ranged from 0.91 to 0.99. This method of predicting individual neck muscle volumes has the advantage of using only one sex-specific regression equation and one set of sex-specific volume proportions. These data can be used in biomechanical models to estimate muscle forces and tissue loads in the cervical spine.

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1. Introduction

Neck muscle volume data are needed for most computational neck models because the volume can be used to estimate a muscle's peak force. Biomechanical models often assume that peak muscle force is proportional to physiologic cross-sectional area (PCSA), and PCSA is estimated from the ratio of muscle volume to optimal muscle fiber length (Spector et al., 1980; Zajac, 1989).

Neck muscle volumes are commonly estimated from cadaveric morphometry studies (Kamibayashi and Richmond, 1998) or from *in vivo* magnetic resonance imaging (MRI) data by tracing the muscle boundaries (Chancey et al., 2003; Oi et al., 2004; Van Ee et al., 2000). In previous studies, the neck muscle volumes obtained from young healthy volunteers by MRI were larger than those from elderly cadavers, likely due to age related atrophy, peri-mortem atrophy and post-mortem desiccation in the cadavers (Chancey et al., 2003; Delp et al., 2001). A disadvantage of both approaches, however, is that they are expensive and time-consuming.

Our goal was to determine if neck muscle volumes could be estimated accurately from external measurements rather than MRI. Burnett et al. (2007) have related the MRI-based volume of seven neck muscles to external anthropometric measurements using seven regression equations—each with a different set of anthropometric parameters. These regression equations were the same for males and females even though other work has shown that males and females have significantly different head and neck geometry and neck strength (Vasavada et al., 2008a). Sex differences have also been found in the size of the limb muscles (*e.g.*, thigh and elbow) and total skeletal muscle mass (Abe et al., 2003; Akagi et al., 2010; Chen et al., 2011). However, the sex differences in neck muscle size have not been investigated according to our knowledge.

In this study, we propose a simple, inexpensive and noninvasive approach to predict individual neck muscle volumes: first by predicting the total neck muscle volume from subject sex and anthropometry; and then by predicting the individual neck muscle volumes using sex-specific proportions of total muscle

* Correspondence to: Voiland School of Chemical Engineering and Bioengineering, Department of Veterinary and Comparative Anatomy, Pharmacology and Physiology, Washington State University, Pullman, WA 99164-6520, USA.
Tel.: +1 509 335 7533; fax: +1 509 335 4650.
E-mail addresses: vasavada@wsu.edu,
vasavada@vetmed.wsu.edu (A. Vasavada).

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volume. We hypothesized that (1) total neck muscle volume can be predicted from sex-specific regression equations based on anthropometric data, and (2) the volume proportion of the individual neck muscles among the total neck muscle volumes is sex specific.

2. Methods

2.1. Subjects

Seventeen subjects (6 females, 11 males) underwent magnetic resonance imaging (MRI) at either Washington State University or the University of British Columbia. Subjects with a history of neck musculoskeletal disorders, metal implants, or pregnancy were excluded. The use of human subjects was approved by the Washington State University Institutional Review Board and the University of British Columbia Clinical Research Ethics Board, and all subjects provided informed consent. Each subject's height, weight, neck length, neck circumference and head circumference were measured (Table 1). The average age of the subjects was 30 years, and the range was 20–46 years for male subjects and 23–43 years for female subjects.

2.2. MRI

Axial proton density-weighted MR images were obtained from the occiput to the T2 or T4 spinal level. Slice thickness/gap ranged from 3.0/0.3 mm to 5.0/1.0 mm among subjects. The image field of view included the trapezius muscle to its lateral border on the acromion process in 11 subjects (8 males and 3 females); in the other 6 subjects (3 males and 3 females), the field of view was smaller, and the lateral part of trapezius was not completely imaged. For the 11 subjects with the larger field of view, a wooden jig (Vasavada et al., 2008b) or foam pads were used to hold the subject's head and neck in the neutral posture (the Frankfurt plane – the plane including the tragus of the ear and the inferior border of the orbit – was vertical while the subject was lying horizontal). In the other 6 subjects, there was no padding behind the head, resulting in a slightly extended posture.

2.3. Data analysis

2.3.1. Neck muscle volumes and total neck volume calculation

Neck muscle boundaries (Fig. 1) were outlined manually on each MRI slice, and the muscle volumes were estimated by integrating the cross-sectional muscle areas (colored areas in Fig. 1) over slice thickness. The total neck muscle volume was the sum of all individual neck muscle volumes. The individual muscle volume proportion was the ratio of each individual muscle volume to the total neck muscle volume.

The neck region (Fig. 2) for each subject was defined from the base of the skull to the slice just superior to the second thoracic vertebrae (T2). The total neck volume (from the base of the skull to T2 level) was estimated by multiplying the traced neck length ((total number of traced slices − 1) × (slice thickness + gap)) by the neck circumference around C4 (Table 1). The volume of most neck muscles was calculated from their superior attachment to the last slice above T2. Sternocleidomastoid and infrahyoids, however, were traced down to the level of their sternal attachment.

2.3.2. Neck muscle volume estimation

The approach to estimate the individual neck muscle volumes involved two steps and used the muscle data from only 10 of the 11 subjects who had complete neck muscle MRI data (Table 1); one male subject was left for validation. First, the total neck muscle volume was predicted from the anthropometric data using the R^2 selection method (SAS Institute Inc., 2010), which performs all possible subset regressions and displays the models in decreasing order of R^2 magnitude within each subset size. Individual predictors screened were sex, height, $(\text{height})^2$, weight, neck circumference, $(\text{neck circumference})^2$, head circumference and neck length. In addition, predictors which were combinations of these factors were also screened: body mass index (BMI: mass/height^2), height^2 × weight, (neck length) × (neck circumference)^2, and (neck length)/(neck circumference). Second, the individual neck muscle volume was obtained from the predicted total neck muscle volume (based on the best regression) and the individual neck muscle volume proportion.

2.3.3. Statistics for sex differences

T-tests were used to study the sex differences in muscle volume data: the total neck muscle volume, the total neck volume, the ratio of total neck volume to the total neck volume, and the individual muscle volume proportion. Equal or unequal variance *t*-tests were used based on the results of an *F*-test for equality of the variances.

2.4. Validation

The estimation procedure for individual muscle volumes was validated in two ways: using one subject with complete neck muscle volume data from MRI, and using six other subjects (Table 1) with all neck muscle volumes except trapezius. The agreement between the regression-predicted muscle volumes and MRI-estimated muscle volumes was assessed using the coefficient of concordance (ρ_c; Lin, 1989):

$$\rho_c = \frac{2\rho\sigma_x\sigma_y}{\sigma_x{}^2 + \sigma_y{}^2 + \left(\mu_x - \mu_y\right)^2} \tag{1}$$

where μ_x and μ_y are the means for the two variables, $\sigma_x{}^2$and $\sigma_y{}^2$ are the corresponding variances, and ρ is the correlation coefficient between the two variables.

Table 1
Anthropometric data, grouped by those subjects with complete muscle data including trapezius (10 of 11 used in model development), and those lacking trapezius data (used for validation). Data shown are the average ± standard deviation, with the range in parenthesis. Neck length was defined as the vertical distance between the C7 spinous process and the tragus, measured using a wall-mounted stadiometer. Neck circumference was the average of the circumferences above and below the thyroid cartilage. Head circumference was the maximum circumference measured with a tape passing over the superciliary ridge and the opisthocranion. Percentile data are provided according to the data of Gordon et al. (1989); however, Gordon's definition of neck circumference was slightly different: circumference at the infrathyroid landmark. Head circumference data were not available for all subjects in the group without trapezius data.

All muscle data	**Female**		**Male**	
	***n* = 3**	**Percentile**	***n* = 8**	**Percentile**
Age (years)	29.9 ± 10.8 (23–43)		31.6 ± 8.7 (20–46)	
Height (cm)	165.1 ± 5.1 (161.2–170.9)	*40%–89%*	174.8 ± 7.9 (161.1–184.0)	*1%–89%*
Weight (kg)	68.0 ± 7.7 (60.7–76.0)	*47%–94%*	75.2 ± 7.2 (65.3–87.3)	*11%–79%*
Neck length (cm)	11.3 ± 0.9 (10.6–12.4)	*78%–99%*	11.8 ± 1.9 (9.3–14.5)	*13%–100%*
Neck circumference (cm)**	34.5 ± 1.3 (33.3–35.9)	*87%–100%*	39.1 ± 1.9 (36.9–43.0)	*30%–99%*
Head circumference (cm)*	56.4 ± 1.0 (55.6–57.6)	*76%–97%*	58.6 ± 1.4 (56.3–60.0)	*88%–100%*
No trapezius data	*n* = 3		*n* = 3	
Age (years)*	29.7 ± 1.2 (29–31)		25.7 ± 2.1(24–28)	
Height (cm)*	166.2 ± 5.3 (160.0–169.5)	*33%–85%*	178.0 ± 3.5 (174.0–180.0)	*41%–75%*
Weight (kg)	67.7 ± 5.8 (61.0–71.0)	*49%–86%*	79.3 ± 7.4 (71.0–85.0)	*26%–74%*
Neck length (cm)**	11.1 ± 0.6 (10.5–11.7)	*75%–96%*	13.0 ± 0.3 (12.6–13.2)	*97%–100%*
Neck circumference (cm)	34.0 ± 1.5 (32.4–35.3)	*72%–98%*	36.5 ± 2.1 (35.0–38.9)	*6%–70%*

* Sex differences noted by $0.01 \le p < 0.05$
** Sex differences noted by $p < 0.01$.