Magnetic resonance imaging-based relationships between neck muscle cross-sectional area and neck circumference for adults and children

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Abstract

Background Computer models and human surrogates used to study the forces and motion of the human neck under various loading conditions are based solely on adult data. Pediatric computer models and dummy surrogates used to improve the safety of children could be improved with the inclusion of previously unavailable pediatric muscle data.

Methods Measurements of neck circumference and neck muscle cross-sectional area (CSA) were taken from ten 50th percentile adult male and ten 10-year old male volunteer subjects. Muscle cross-sectional areas were calculated from magnetic resonance images of axial cross-sections of the neck.

Results Neck muscle cross-sectional area was calculated for six muscles/muscle groups. A power-law regression analysis was used to describe the relationship between neck circumference and neck muscle cross-sectional area.

Conclusions The cross-sectional area and the power-law functions determined by the data in this study provide a means of calculating muscle cross-sectional area for young

children, where such data are currently unavailable. This will provide an opportunity to develop more representative pediatric neck models.

Keywords Magnetic resonance imaging · Pediatric · Neck muscles · Cross-sectional area

Introduction

Finite element models have become more sophisticated in both detail and their ability to predict human responses to various loading conditions. More recently, these models in the neck have been developed to incorporate not only the bony structure of the cervical spine, but also the mechanical properties and geometries of the soft tissues [1, 10, 20]. The models have, however, been predominantly adult models. The difficulty of obtaining accurate pediatric data complicates the development of pediatric finite element models and muscle optimization models. The ability of these models to predict the behavior of the neck under various loading conditions provides a means of preventing neck injuries.

Although the occurrence of neck and spinal cord injuries in children is relatively low, accounting for only 1–2 % of all reported injuries, the implications of injuries are significant [2, 4, 9, 20]. Retrospective studies conducted at level 1 trauma centers in both Canada and the United States show that children (ages 0–12 years) sustaining spinal injuries have a higher mortality rate (17 %) than adults [2, 9], a higher rate of permanent spinal cord injury [19], longer hospitalization time [7], and a higher rate of traumatic brain injuries [2, 3, 8, 19] than adults. Traumatic head injuries were present in 94 % of the spinal injuries cases reported [2, 4, 9, 20]. In many cases, brain injury was

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considered to be the cause of death. Given the severity of closed head injuries in children injured in a motor vehicle accidents, Brown et al. [2] have proposed that the occurrence of neck injuries may be overlooked and underreported.

Due to an upward shift in the center of rotation of the neck of children as it flexes/extends [4, 11, 20] and due to their proportionately larger heads, child neck injuries tend to occur between the occiput and C4. In adults, neck injuries are more likely to occur below C4 [2, 4, 9, 11, 20]. From the collected MRI data, a mathematical relationship between neck CSA and muscle CSA is proposed. This would provide a means of determining muscle geometry for all ages for use in the development of accurate finite element models. Furthermore, models developed at this common injury location (C4) would provide insight into differences in muscle responses. Choi et al. [5] developed a mathematical model at C4 to determine the forces generated in the neck muscles of adults under static loading conditions. Their muscle geometry was based on data provided by Moroney et al. [14] at the C4-spinal location. In other studies, the cross-sectional area (CSA) of adult neck muscles was calculated at C4–5, at the intervertebral disc between the C4 and C5 vertebral bodies, to determine whether chronic headaches and neck pain are related to changes in muscle CSA. DeLoose et al. [6] studied the neck muscle CSA at C4–5 of fighter pilots with chronic neck pain, while Oksanen et al. [16] studied the CSA of young adults with chronic headaches.

The purpose of this study was to determine the anatomical CSA of the sternocleidomastoid (SCM), the trapezius (TRAP), the splenius capitis (SPL), and the scalene muscles (SCAL) as well as the anatomic CSA of the posterior and postero-lateral neck muscle groups for 50th percentile adult males and 50th percentile 10-year-old males at the C4 spinal level. Since this level is a common injury location, muscle CSA data collected at this location could be used in models similar to the Choi et al. model [5] and would provide the first baseline data for studies in young children similar to the data collected in adults.

Methods

Subject selection was limited to healthy, normally active adult males and boys of age 9–11 years that had no prior history of neck injury, chronic neck pain, or neuromuscular disorders. Subjects in this study were screened to meet the height and weight criteria of a 50th percentile individual per the findings of the National Health and Statistics report published in 2005 [12]. Adult male subjects were considered to be 50th percentile if they weighed 77.3 ± 5 kg and were 170–175 cm in height. Boys, 9–11 years old, weighing 35.2 ± 1 kg, and 125–130 cm in height were recruited for

this study. The range of weight and height stipulated for this study is consistent with the published specifications for the 50th percentile adult male Hybrid III and the 10-year-old Hybrid III anthropometric test devices (ATD's). Subjects were recruited in these ranges so that muscle response data developed in mathematical models are comparable to response data of the 50th percentile adult male and child anthropometric test devices (ATD's). Participants were also screened for contraindications to MRI, including but not limited to orthopedic implants and claustrophobia.

This research plan was approved by the Institutional Human Investigation Committee (HIC). Adult subjects gave informed, signed consent. Child subjects involved in the study gave informed, verbal assent. The parent/guardian of each child subject gave signed consent for their child's participation in the study.

Magnetic resonance imaging

A 1.5 T Siemens Sonata Magnetic Resonance Scanner was used to image the neck muscles of each subject in the study. In order to maximize the contrast between the muscles and the surrounding tissues, all sequences were T1 weighted fat-saturated images. A voxel size of $0.5 \text{ mm} \times 0.5 \text{ mm} \times 5 \text{ mm}$ was used in all sequences. Four imaging sequences in addition to the initial localizing sequence were used to image the neck of each subject from the top of the head to the second thoracic vertebra. Three of the four sequences were 56-slice sequences in the axial plane. The first sequence sliced the neck in the true anatomical axial plane. The second and third axial sequences were sliced perpendicular to the line-of-action of the SCM and the scalene muscles, respectively. The fourth sequence, a 32-slice sequence, imaged the neck in the sagittal anatomic plane. Time was a consideration for determining the imaging protocol, since children were being used as subjects in this study. Sedation was not used in the research protocol.

Subjects were placed supine in the magnet with their legs and back parallel to the ground. Support for the lower back was provided by placing pillows under the subject's knees. The subject's neck was similarly supported in a comfortable position using padding. A circularly polarized (CP) head/neck and spine coil combination was placed over the subject's neck which served to augment the imaging signal in the neck region. Subjects were given earplugs to help reduce the noise made by the imager. Music was played during imaging to help subjects relax. Imaging time was approximately 15 min. The imaging protocol was developed to provide maximum information in a short amount of time to accommodate the children in the study.

The neck circumference of each subject was measured prior to imaging with a cloth measuring tape. Neck circumference was measured at C4; the measurement location

Fig. 1 **a** Single image slice showing the anatomical cross-sectional area (ACSA) muscle boundaries for a 50th percentile adult male subject. The slice shown was taken at the mid-point of the C4 vertebrae where SCM shows the sternocleidomastoid cross-sectional area, SCAL shows the combined scalene muscle group cross sectional area, TRAP shows the trapezius cross-sectional area, and SPL shows the splenius capitis cross-sectional area. **b** CSA for 10-year-old, also taken at the midpoint of the C4 vertebrae—to illustrate the difference in geometry and the muscles that needed to be combined in this age group

was determined by palpating the spinous processes of the spine.

Muscle cross-sectional area measurement

Proprietary software (SPIN, Detroit, MI, USA) was used to calculate to anatomical CSA of the SCM, TRAP, SPL, SCAL, the posterior neck muscles (POST), and the

postero-lateral neck muscles (P-L). The posterior muscles included the trapezius, splenius capitis, splenius cervicis, semispinalis capitis, semispinalis cervicis, and multifidus. The postero-lateral muscles included the longissimus and levator scapula. The scalene muscles included the scalene muscles and the longuscolli, and cervicis.

Image slices were consistent between subjects. The slice used was compared with published images [6, 14, 18] to ensure that it corresponded to the correct spinal level. In this study, muscle CSA was measured at the mid-point of the C4 vertebral body.

Anatomic CSA was calculated inside the boundary manually placed around the perimeter of each muscle/muscle group. SPIN determined the number of pixels within the boundary. Area was calculated by multiplying the number of pixels by the single pixel area of 0.5 mm × 0.5 mm (Fig. 1).

Statistical analysis

A non-linear regression was used to determine the goodness of fit of the power function curve applied to the neck muscle CSA data. A Chi-squared statistical analysis was used to determine significance. $P < 0.05$ was considered significant.

Results

The anatomical muscle cross-sectional area results at C4 for both 50th percentile adult males and 50th percentile 10-year-old boys are shown in Tables 1 and 2. To determine a relationship that would provide a means of determining the muscle cross-sectional areas of subjects, particularly children, of other ages, muscle cross-sectional area CSA was plotted with respect to neck circumference, with muscle CSA being the dependent variable (Fig. 2). With the exception of the scalene muscles, the relationship between neck circumference and muscle CSA is described by a second-order power-law function ($P < 0.05$). The equations describing the relationship of the muscle CSA to the neck circumference were determined using the “trend line” function in MS Excel. The equations shown in Fig. 2 are based on a best-fit power-law regression analysis. In order to verify the second order power-law function shown in Fig. 2, the neck was idealized as a circle. Circle circumference ranged from 0 to 40 cm, capturing the neck circumference values of the subjects in this study. Cross-sectional area was expressed as a percentage of the circle area; this percentage was based on the percentage of that total neck CSA that is represented by muscle. Using the imaging data, total muscle content was estimated as 43 % of the total neck CSA. The graph of circle circumference

Table 1 Neck circumference and calculated muscle cross-sectional area values for 50th percentile adult male subjects for the sternocleidomastoid (SCM), trapezius (TRAP), splenius capitis (SPL), scalene muscles (SCAL), the posterior neck muscles (POST) which included

trapezius, splenius capitis, splenius cervicis, semispinalis capitis, semispinalis cervicis, and multifidus; and the postero-lateral muscles (P-L) which included longissimus and levator scapula

Subject	Age	Neck circ (cm)	Anatomic CSA at C4 (cm ²)					
			SCM	TRAP	SPL	SCAL	POST	P-L
S08	29.0	37.5	4.71	4.96	3.08	1.12	13.02	
S09	37.0	36.7	4.87	2.71	2.50	1.32	11.54	5.38
S10	28.0	43.0	6.90	5.09	2.57	1.19	13.13	7.28
S11	24.0	35.5	5.96	2.48	3.00	1.59	10.30	4.35
S13	29.0	39.0	5.51	2.53	2.43	1.17	13.38	4.72
S14	26.0	36.0	5.40	3.06	2.60	1.45	11.94	5.79
S15	40.0	36.5	4.86	2.70	2.22	1.04	12.69	4.23
S16	47.0	38.5	4.17	2.06	2.52	0.96	9.83	4.45
S17	54.0	41.0	5.08	3.19	2.47	1.28	14.47	5.47
S20	42.0	38.0	5.13	2.80	1.99	1.42	13.95	5.54
Average	35.60	38.17	5.26	3.16	2.54	1.25	12.42	5.25
SD	10.01	2.34	0.76	1.03	0.32	0.20	1.51	0.96

Table 2 Neck circumference and calculated muscle cross-sectional area values for 50th percentile 10-year-old male subjects for the sternocleidomastoid (SCM), trapezius and splenius capitis (TRAP + SPL), scalene muscles (SCAL), the posterior neck muscles (POST)

which included trapezius, splenius capitis, splenius cervicis, semispinalis capitis, semispinalis cervicis, and multifidus; and the postero-lateral muscles (P-L) which included longissimus and levator scapula

Subject	Age	Neck circ (cm)	Anatomic CSA at C4 (cm)				
			SCM	TRAP + SPL	SCAL	POST	P-L
K01	10.0	28.8	2.84	3.44	0.96	6.15	3.10
K03	10.0	32.2	3.28	4.59	1.20	8.58	3.88
K04	10.0	29.5	2.87	2.30	1.14	5.68	2.66
K05	11.0	32.0	3.65	3.62	0.97	6.30	2.92
K06	11.0	28.5	3.76	3.41	0.78	8.08	3.61
K07	10.0	31.0	3.76	1.58	0.71	7.45	3.37
K08	10.0	30.0	2.82	1.76	0.80	9.31	3.61
K09	9.5	31.0	3.55	3.51	0.79	8.15	2.41
K10	10.0	30.0	3.27	2.46	1.03	7.35	2.93
K11	10.0	27.5	3.46	2.20	0.78	6.88	2.44
Average	10.15	30.05	3.33	2.89	0.92	7.39	3.09
SD	0.47	1.53	0.37	0.97	0.17	1.16	0.51

from 0 to 40 cm versus the percentage of the circle CSA of the circle representing total muscle CSA (43 %) showed that CSA was proportional to the square of the circle circumference. These data were overlaid with the actual study data; the study data showed a strong correlation with the idealized, circle data ($r^2 = 0.819$), shown in Fig. 3.

Discussion

Due to the lack of pediatric neck muscle morphology and strength data, accurate mathematical models of pediatric

necks of varying ages and sizes are difficult to develop. This study provides anatomic muscle cross-sectional area data at C4 and suggests a relationship to determine neck muscle CSA based on the non-invasive measurement of neck circumference. The validity of the relationship is dependent on the accuracy of the measured neck muscle CSA's.

Physiologic cross-sectional area (PCSA) was not calculated in this study. While PCSA is more commonly used in computer based modeling [19] to determine the kinetic and kinematic neck responses due to various loading conditions, the CSA of each individual muscle could not be

Fig. 2 Graph showing the relationship between neck circumference and the cross-sectional area of the muscle or muscle groups measured in the study in the axial C4 plane. *SCM* sternocleidomastoid cross-sectional area, *TRAP + SPL* trapezius and splenius capitis cross-sectional area, *SCAL* scalene muscle cross-sectional area, *POST* posterior muscle group cross-sectional area, *P-L* postero-lateral muscle group cross-sectional area. The best-fit power function of the neck circumference to muscle CSAs is also shown

Fig. 3 Idealized circle data showing the power relationship between cross-sectional area and circumference overlaid with the total muscle cross-sectional area values calculated from the study's MR-images, the individual subject neck circumferences, and the best-fit power function of this relationship. The R^2 shown for the study data reflects the relationship between the idealized regression and the study data regression

calculated over the entire length of the muscle due to difficulties in determining the individual muscle boundaries. This was particularly valid for the child subjects where the neck showed very little intramuscular fat. To date, computer models of the neck have only been developed for adults.

The adult muscle cross-sectional area data that were collected in this study, with the exception of the trapezius,

were similar to the muscle cross-sectional areas published for the same spinal location in other studies [6, 16, 18] as shown in Table 2. All three studies shown in Table 2 used T-1 weighted imaging sequences with slice thickness ranging from 3 to 4 mm. Results are for a single slice at the C4/5 spinal level; specifically, muscle cross-sectional areas shown in Table 2 for the Oksanen, Stemper and DeLoose studies [6, 16, 18] were taken at the midpoint of the

Table 3 Comparative anatomical cross-sectional area data published in the literature

Study/Reference	CSA (cm ²)			
	SCM	Trapezius	Splenius capitis	Scalene muscles
Anatomic cross-sectional area				
Oksanen et al. [16]				
R	5.02 (SD 0.68)	1.46 (SD 0.71)	2.84 (SD 0.34)	1.13 (SD 0.27)
L	5.26 (SD 0.61)	1.68 (SD 0.79)	2.94 (SD 0.35)	1.2 (SD 0.26)
DeLoose et al. [6]				
R	5.93 (SD 1.07)	3.97 (SD 1.05)	2.73 (SD 0.77)	1.17 (SD 0.29)
L	6.28 (SD 1.09)	4.32 (SD 1.40)	2.89 (SD 0.70)	1.16 (SD 0.32)
Stemper et al. [17]	5.65	1.25		
Dawson study data (ACSA at C4/C5)	5.26 (SD 0.76)	3.16 (SD 1.03)	2.54 (SD 0.32)	1.25 (SD 0.20)

intervertebral disc between the C4 and C5 vertebrae, and in our study CSA measurements were taken at the mid-point of the C4 vertebral body. This may account for some of the differences in their results as compared with those reported in this study.

Height, weight, and level of physical activity may also account for some of the differences between the measurements, particularly the DeLoose and Oksanen studies. The subjects in the DeLoose study were physically fit fighter pilots whose height and weight range were higher than the subjects in this study. The Oksanen study by contrast used both male and female subjects so average height and weight were lower than the height and weight of subjects in this study. Height and weight differences, however, do not account for all the differences. Although the trapezius muscle boundary is generally visible, it is possible that the CSA of this study includes other posterior neck muscles. This study's imaging protocol was developed to maximize the data discernable from the image while reducing the time spent in the magnet since there were child subjects involved in the study. Other studies were not faced with the same restriction which would enable longer scan times and clearer images (Table 3).

The only comparative child data available are the results of a doctoral study by Miller et al. [13] in which the CSA of the extensor muscles of the neck was calculated for children of all ages. For children aged 6–10 years Miller et al. report a CSA of 8.77 cm² (SD 1.35 cm²), a 16 % difference from the posterior muscle CSA reported in this study. However, the Miller CSA includes the scalene muscles in the area of the posterior muscles. When the child posterior muscle CSA is combined with the child scalene muscle CSA results, the percent difference drops to 5 %.

Zero-intercept power functions were proposed in this study to describe the relationship between each neck muscle/muscle group cross-sectional area and neck circumference. The zero-intercept model was used because it

realistically models the zero muscle CSA for zero neck circumference. Other functions with an intercept erroneously calculate muscle cross-sectional area values for a zero neck circumference. Furthermore, the zero-intercept function provides reasonable values of muscle cross-sectional area for the infant neck circumference. Other types of intercept functions under/over-estimate these values. An estimate of an infant's neck circumference was found using information from a medical supply distribution company, Southwest Medical, Arizona, USA.

The power-law functions, shown in Fig. 2, showed that muscle CSA is proportional to the square of the neck circumference (SD 0.5). For the only exception, the scalene muscles, the analysis showed that their muscle CSA was proportional to almost the cube of the neck circumference. This may be due to an overly large calculated muscle CSA stemming from difficulties in determining the muscle boundaries, particularly in the pediatric group where the amount of intramuscular fat was small. Cagnie et al. [3] developed a pixel intensity profile, in which fatty tissue had high pixel intensity, as a means of determining the amount of fat contained within a particular muscle. A similar approach for determining intramuscular boundaries could provide more accurate CSA results. Although the actual data collected during the imaging study showed a good fit with the idealized data ($P < 0.05$), the addition of a third age group, in particular a younger age group, would add further robustness to the curve.

A similar relationship was developed in a study by Knapik et al. [8] which related thigh muscle cross-sectional area to the circumference of the thigh. Their study also showed that muscle cross-sectional area was proportional the square of the thigh circumference. Fat thickness and the distance between the medial and lateral epicondyles were also included in their equation. In a 10-year longitudinal study of neck muscle CSA at various spinal levels, Okada et al. [15] showed increasing neck muscle CSA with

respect to increasing age until the fourth decade. Beyond the fourth decade, neck muscle CSA begins to decrease. These results are consistent with the finding of this study which showed higher CSA of all neck muscles studied in the adult males compared to those of the 10-year-old boys.

The results of this study and the relationship between muscle CSA and neck circumference would provide a means for developing pediatric neck models, similar to those models developed for adults by Vasavada et al. [19] and VanEe et al. [18]. While computer models have made it easier to determine the kinematic and kinetic responses of the adult neck under various loading conditions, the lack of child muscle data has made it difficult for similar pediatric models to be developed. Given the frequency and severity of head and neck injuries in children, these models would provide a cost-effective way of understanding neck responses in children. Similarly, the data developed in this study could also be used to help determine the strength and stress responses of the pediatric neck.

Conclusions

The power-law regression analysis between neck circumference and muscle cross-sectional area proposed in this study provides a means to estimate the neck muscle cross-sectional areas of average, healthy individuals without using potentially expensive imaging techniques. This is particularly significant for young children, where muscle morphological data are not readily available and imaging protocols can be time consuming, stressful, and may require sedation.

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Conflict of interest None.

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