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Sex and posture dependence of neck muscle size-strength relationships

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ABSTRACT

Neck muscle size and strength have been linked to lower injury risk and reduced pain. However, prior findings have been inconclusive and have failed to clarify whether there are sex differences in neck muscle size-strength relationships. Such differences may point to an underlying cause for the reported sex difference in neck pain prevalence. Thirty participants (13 males, 17 females) who underwent neck strength testing and MR imaging were analyzed. Strength was measured in three conditions that differed in posture and exertion direction. Muscle size was quantified by three metrics: anatomical cross-sectional area (ACSA), muscle volume (MV), and an estimate of physiological cross-sectional area—reconstruction-based cross-sectional area (RCSA). Inter-posture strength correlations, muscle size-strength correlations, and sex differences were analyzed with linear regression. Males were approximately 65% stronger and had significantly larger muscles. Strength varied significantly across postures, but only female strength values for different postures were significantly correlated. Observed in males only, the sternocleidomastoid (SCM) was a strong predictor of flexion strength in the neutral posture while the anterior scalene (AS) was more involved in the extended. No extensor's size was significantly linked to extension strength. A greater amount of force variation is unexplained by muscle size alone in females than in males. Males and females exhibited distinct size-strength relationships, highlighting the need for sex-specific models and analyses and the greater potential effect of non-morphometric factors on force generating capacity in females. No advantage of one muscle size metric over another in strength prediction was evidenced.

1. Introduction

Neck pain is growing in prevalence, health care expenditure, and years lived with disability (Dieleman et al., 2016; Hoy et al., 2014; Hoy et al., 2010; Hurwitz et al., 2018; Murray et al., 2013). The global prevalence of neck pain is estimated to be 4.9% and is considerably higher in women (5.8% prevalence) than men (3.9% prevalence) (Hoy et al., 2014; Vos et al., 2012). Among a multitude of factors that may play a role in the causation and control of neck pain and injury, neck strength and muscle size have more demonstrable effects and are readily measurable. Studies have used dynamic impact simulations, static strength tests, and muscle measurements to explore relationships that can inform protective or interventional strategies (Collins et al., 2014; Eckner et al., 2014; Gilchrist et al., 2015; Hrysomallis, 2016; Schmidt et al., 2014). Evidence from laboratory research in this area has been consistently suggesting an inverse relationship between neck strength and head acceleration (Caccese et al., 2018; Gutierrez et al., 2014; Jin et al., 2017; Mansell et al., 2005). Neck muscle size and strength have also been found to decrease in patients with chronic neck pain and increase during successful therapy (Amiri Arimi et al., 2018; Barton and Hayes, 1996; Cagnie et al., 2007a; Silverman et al., 1991; Ylinen et al., 2007; Ylinen et al., 2003). However, translation of these findings into neck pain or injury incidence prediction has shown mixed results (Mihalik et al., 2011; Salo et al., 2012; Schmidt et al., 2014). This gap highlights the need for a clearer understanding of the role of neck muscle and strength in injury biomechanics (Fukushima et al., 2006; Guskiewicz et al., 2007; Honda et al., 2018; Le Flao et al., 2018; Lisman et al., 2012; Viano et al., 2007).

Studies investigating the role of specific musculature in strength build on the accepted linear relationship between muscle size and joint force production capacity (Balshaw et al., 2017; Jones et al., 2008). Such relationships have been constructed to compare young versus old or trained versus untrained (Akagi et al., 2018; Akagi et al., 2009; Alway et al., 1996; Bruce et al., 1989; Castro et al., 1995; Young et al., 1985). Anatomical cross-sectional area (ACSA) measured by ultrasonography, the fastest and most accessible method of quantifying muscle size, has

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been utilized in prior strength analyses (Schmidt et al., 2014). Muscle volume (MV), measured from MRI, has been shown to be a better determinant of arm strength than ACSA, though this has yet to be evaluated for the neck muscles (Akagi et al., 2009; Fukunaga et al., 2001; Holzbaur et al., 2007a). Prior investigations of size-strength relationships lumped a single regression model without separating males and females in spite of the bimodal distributions of both strength and size (Holzbaur et al., 2007a). Such an approach inflates the correlation strength and does not allow for sex-specific analyses and insights, while sex differences have been reported not only in neck pain incidence but also in neck impact injury risk, persistency, and treatment outcome (Berglund et al., 2006; Côté et al., 2004; Dolinis, 1997; Guez et al., 2002; Hendriks et al., 2005; Hoy et al., 2010).

Motivated by the belief that prolonged deviated neck posture is a risk factor for neck pain and the fact that prior injury prediction studies had only evaluated neck strength in a neutral posture, recent investigations have studied neck strength in different directions and non-neutral positions (Ariëns et al., 2001; Cagnie et al., 2007b; Gilchrist et al., 2016; Hildenbrand and Vasavada, 2013; Salo et al., 2006). However, none have studied in depth how different muscles in the neck affect strength in different postures or examined neck flexion strength in an extended head-neck position, a posture commonplace in sports and in occupational environments when overhead work is performed (Heck et al., 2004). Variability in strength across postures may be more complicated than changed muscle length. As Vasavada et al. (1998) showed in a computer modeling study, the sternocleidomastoid (SCM), commonly regarded as the primary neck flexor, exhibits extension moment arms at the skull-C2 and C2-T1 "joints" (as defined by Software for Interactive Musculoskeletal Modeling-SIMM) when in an extended head-neck posture. This provokes the question of whether the agonist-vs-antagonist role of the SCM as well as other muscles may be posture-dependent.

Therefore, the purpose of this study was to elucidate neck muscle size-strength relationships by examining three questions. First, are strength differences between the sexes reducible to muscle size differences? Second, how does a change in posture affect strength prediction from muscle size? Third, how do ACSA and MV compare with a solely MRI-based estimate of physiological cross-sectional area (PCSA) as alternative predictors of neck strength?

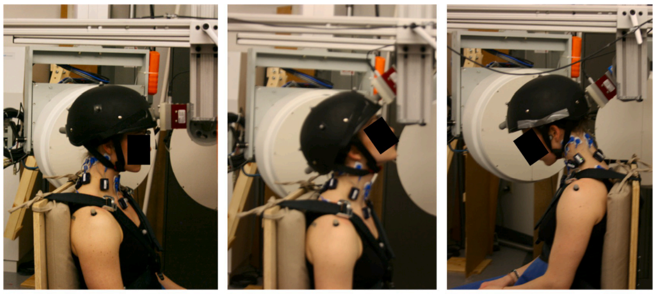
2. Methods

2.1. Participants

Forty healthy adults (20 males, 20 females), aged 21 – 45, free from neck pain or any prior neck injury, were recruited to participate in the study. The study protocol, approved by the Institutional Review Board, was explained in detail to the participants who then provided written consent. Ten participants' data were excluded from the study due to poor MRI or strength measurement quality, leaving 13 males and 17 females for analysis; in particular, nine participants' MRI scans were subject to excessive motion artifact and image blur such that muscle boundaries were indiscernible.

2.2. Strength measurement

A custom-designed testing frame housed a seat and a tri-axial load cell (FUTEK Advanced Sensor Technology, Inc., Irvine, CA) and was made adjustable to accommodate neck exertions in a variety of postures by individuals with a wide range of anthropometry (Fig. 1). More detailed descriptions of this testing apparatus are available in prior publications (Chowdhury et al., 2021; Zhou et al., 2020). Participants were secured to the seat with a four-strap harness and were fit with an appropriately sized (out of three sizes) Daytona half-shell helmet (Ennis Kirk, Inc., Rush City, MN) with interior padding and a chin strap. 3D printed plastic hemispheric protrusions were mounted to the front and back of the helmet and were designed to mate with a spherical concavity attached to the load cell to prevent slipping and permit quick disengagement. After an initial warmup, participants performed neck exertions in three conditions: (A) flexion in a neutral posture, (B) flexion in 40° of head-neck extension, (C) and extension in 40° of flexion. The 40° angle, measured as the angle between the Frankfort plane and the horizontal, was chosen so that the postural deviation would be substantial enough to evoke a salient effect yet achievable by all participants with varied neck ranges of motion. In each condition, participants performed four exertions with maximal voluntary intensity, two for a minimum of 5 s and two sustained-till-exhaustion. The sustained trials were included in strength analysis to account for the difficulty and novelty of neck exertions by affording participants a longer time window for maximal force production (Sommerich et al., 2000). Ample rest of at least twice the duration of the prior trial was given between exertions. Resultant force data from the load cell were smoothed with a 50 ms moving average window. Strength for a given trial was determined by identifying the 0.5 s interval during which the greatest force was produced and taking the average force across the interval (Holzbaur et al., 2007a). Participant strength in a given posture was determined as the highest strength value out of all four trials in that posture.



(A) Neutral (B) 40º Extended (C) 40º Flexed

Fig. 1. The adjustable frame and seat were custom-designed to accommodate participants with a broad range of anthropometry. The experimental apparatus allowed six ways of translational adjustment (3 directions for load cell positioning, vertical frame adjustment, and both vertical and anteroposterior movement of the seat) and two degrees of rotational freedom (about the mediolateral axis for the load cell to permit flexion/extension changes and about the vertical axis for the swivel-chair to permit both anterior and posterior exertions). Neck strength was tested in three conditions: (A) anterior exertion in neutral posture; (B) anterior exertion in 40° extended posture; (C) posterior exertion in 40° flexed posture. The flexion–extension angle was measured by the Frankfort plane (as defined by motion capture markers placed on tragion and infraorbitale landmarks) relative to the horizontal plane.

2.3. Muscle morphometry measurement

All participants underwent MR imaging at the University of Pittsburgh Medical Center (UPMC) Magnetic Resonance Research Center (MRRC). Axial images of participants' entire necks in a supine posture were captured with a 3 T clinical scanner (proton density-weighted, turbo-spin echo sequence; TE = 9.0 ms; slice thickness = 3.0 mm; no gap). Neck muscle bellies were manually outlined in each MRI slice by one analyst using Mimics 20.0 (Materialise Inc., Ann Arbor, MI) (Fig. 2). In addition to the original 30 scans, MRIs of four randomly chosen participants (two male and two female) were segmented again, no sooner than two months after the original segmentation process, to evaluate segmentation reliability. Fourteen total muscle pairs were segmented as 10 paired muscular groups. The sternocleidomastoid, anterior scalene, infrahyoid, longus capitis and colli, and levator scapula muscles were segmented from C1 to their origins, and all remaining muscles were segmented from C1 to C7. To adapt ultrasonographic ACSA measurement to MRI, ACSA was determined as the largest cross-sectional area of a muscle in any single MRI slice (Eckner et al., 2014;

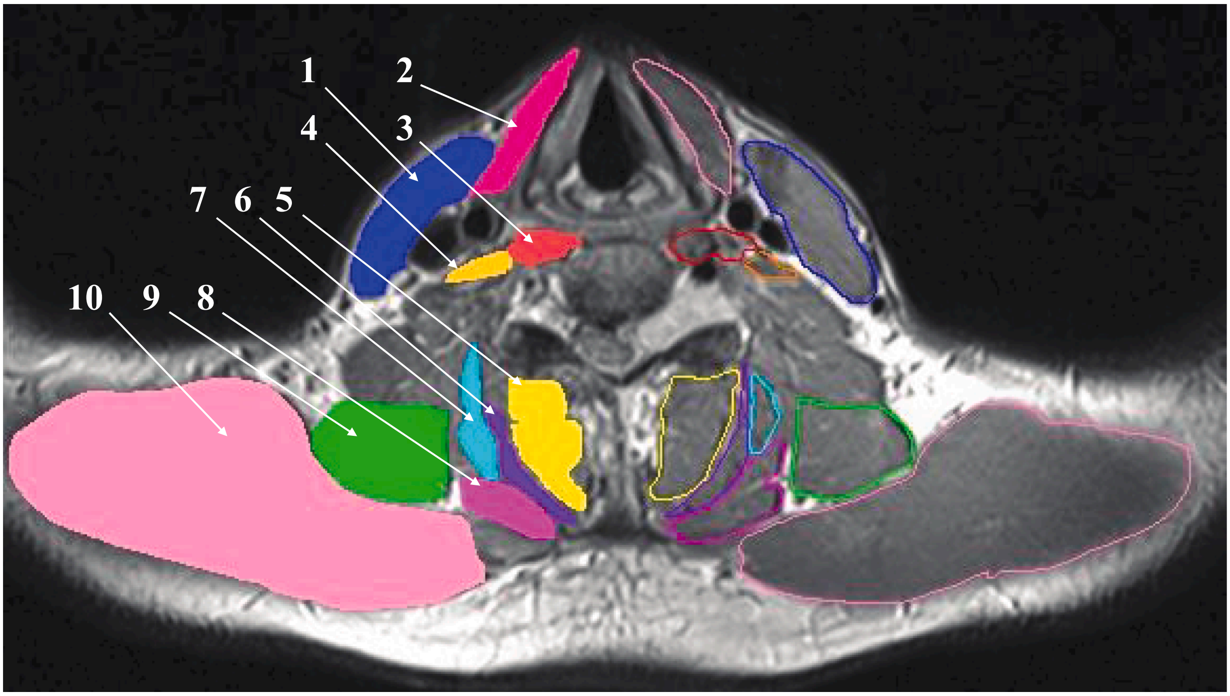


Fig. 2. Segmented muscle bodies in a cross-sectional MRI at the C6 level: 1. sternocleidomastoid (SCM); 2. infrahyoid muscles (IH); 3. longus colli and longus capitis (Longus); 4. anterior scalene (AS); 5. semispinalis cervicis and multifidus (Deep); 6. semispinalis capitis (SSC); 7. longissimus cervicis and longissimus capitis (Longiss); 8. splenius capitis and splenius cervicis (SPL); 9. levator scapula (LS); and 10. trapezius (Trap).

Schmidt et al., 2014). MV was calculated by multiplying the sum of a muscle's segmented area from all slices by slice thickness (Barnouin et al., 2014; Elliott et al., 2007; Holzbaur et al., 2007b; Tingart et al., 2003; Zheng et al., 2013). The calculation of physiological cross-sectional area (PCSA) requires a muscle's optimal fiber length and pennation angle, neither readily accessible with MRI. A novel method was introduced for PCSA estimation without involving generic (i.e., not subject-specific) data. This method calculated muscle length (ML) as the length of a 3D cubic polynomial curve-fitted to the centroids of the segmented MRI slices. A reconstruction-based cross-sectional area (RCSA) was then obtained by dividing MV by ML.

2.4. Statistical analysis

Descriptive statistics of anthropometric measures were obtained for male and female participants separately and were compared using Student's t-tests to test for significant differences in age, height, weight, and BMI. Muscle measurement reliability was determined by calculating percent difference in muscle size between original and duplicate muscle segmentations on a muscle-by-muscle basis and then taking the average percent difference; this was repeated for each morphometric measure. Strength measurement reliability was assessed by calculating intra-class correlation coefficients for each condition (Shrout and Fleiss, 1979). Student's t-tests were used to compare male to female muscle size across the three metrics and to compare male to female strengths in each of the three conditions. The difference of means, δ, and the 95% confidence interval of δ was reported for each anthropometric and strength comparison. Linear regression was used to correlate strength in condition A to strengths in the other two conditions for each sex. Correlation was also used to identify linear relationships between muscle or muscle group size (cm^2 for ACSA, cm^3 for MV, and cm^2 for RCSA) to neck exertion strength (N). Student's t-tests were used to compare male to female regression model coefficients. The relative distance of a size-strength model intercept to 0, as determined by percent confidence interval, was used to evaluate model validity (Bamman et al., 2000; Bruce et al., 1997). Pearson's product-moment correlation coefficient (r) was used to report the strength of linear relationships between strength measures and of muscle size-strength relationships. The coefficient of determination (R^2) was used to quantify the amount of variance in strength explained by the variance in muscle size.

3. Results

3.1. Anthropometry and muscle morphometry

A comparison of anthropometric measures between male and female participants found height to be the only significantly ($\alpha = 0.05$) different feature between the two (Table 1). Test-retest reliability for muscle size from segmentation was 4.7%, 5.1%, and 6.5% for MV, RCSA, and ACSA respectively. All muscles were significantly larger in males than in females, except for the AS; these findings were similar across muscle metrics (Table 2).

3.2. Strength

On average, female strength was 68.0%, 58.7%, and 70.1% of male strength in conditions A, B, and C, respectively (Table 3). Participants produced significantly more force in condition C than in A and

Table 1
Statistical summary and comparison of age, anthropometry, and BMI between the male and female participants.

	Male (n = 13)	Female (n = 17)	p-Value	Difference (δ)	95% CI of δ
Age	30.5 (±1.7)	30.8 (±1.7)	0.900	−0.30	[-5.19, 4.58]
Height (cm)	174.7 (±2.4)	168.2 (±1.9)	0.045*	6.46	[0.15, 12.77]
Weight (kg)	72.3 (±3.5)	65.7 (±2.5)	0.131	6.51	[-2.05, 15.07]
BMI	23.5 (±0.7)	23.2 (±0.6)	0.690	0.38	[-1.55, 2.31]

Table 2
Comparison of segmented muscle size between the male and female participants.

Muscle Name	Male (n = 13)	Female (n = 17)	*p*-Value	Male (n = 13)	Female (n = 17)	*p*-Value	Male (n = 13)	Female (n = 17)	*p*-Value
	Muscle ACSA (cm^2)			Muscle RCSA (cm^2)			Muscle Volume (cm^3)		
SCM	9.88 (±0.59)	7.06 (±0.35)	<0.001*	5.57 (±0.30)	4.13 (±0.17)	<0.001*	107.9 (±6.4)	72.7 (±3.5)	<0.001*
IH	5.08 (±0.16)	3.38 (±0.14)	<0.001*	3.14 (±0.12)	2.22 (±0.10)	<0.001*	34.5 (±2.0)	22.2 (±0.8)	<0.001*
Longus	4.05 (±0.15)	3.13 (±0.12)	<0.001*	2.33 (±0.07)	1.78 (±0.07)	<0.001*	34.9 (±1.4)	25.5 (±1.2)	<0.001*
AS	3.49 (±0.20)	3.35 (±0.22)	0.646	1.82 (±0.11)	1.77 (±0.12)	0.778	12.4 (±0.9)	12.7 (±1.0)	0.853
Deep	8.05 (±0.33)	6.27 (±0.18)	<0.001*	5.42 (±0.17)	4.19 (±0.13)	<0.001*	37.3 (±2.3)	28.4 (±1.3)	0.001*
SSC	9.86 (±0.33)	6.74 (±0.23)	<0.001*	5.53 (±0.23)	3.69 (±0.13)	<0.001*	60.6 (±3.2)	38.2 (±1.5)	<0.001*
Longiss	2.43 (±0.15)	1.59 (±0.06)	<0.001*	1.15 (±0.05)	0.87 (±0.03)	<0.001*	13.1 (±0.7)	9.5 (±0.5)	<0.001*
SPL	6.95 (±0.36)	5.04 (±0.21)	<0.001*	5.00 (±0.26)	3.66 (±0.14)	<0.001*	55.5 (±3.2)	39.1 (±1.6)	<0.001*
LS	12.69 (±0.74)	9.71 (±0.90)	0.020*	4.46 (±0.16)	3.18 (±0.18)	<0.001*	68.8 (±3.1)	50.1 (±2.7)	<0.001*
Trap	50.07 (±6.78)	26.46 (±4.84)	0.007*	6.51 (±0.69)	3.97 (±0.60)	0.010*	88.1 (±11.5)	46.5 (±8.9)	0.007*

Table 3
Statistical summary and comparison of strength (in Newtons) in each condition between males and females

Condition	Male	Female	*p*-Value	Difference (δ)	95% CI of δ
A	113.8 (±8.3)	77.4 (±6.7)	0.002*	36.4	[14.8, 57.9]
B	74.3 (±6.7)	43.6 (±4.2)	<0.001*	30.7	[15.3, 46.1]
C	159.2 (±9.9)	111.6 (±6.2)	<0.001*	47.6	[24.6, 70.5]

significantly more force in A than in B. For females, strength in condition A was strongly correlated to strengths in non-neutral postures, but no such correlation was found for males (Table 4). Intra-class correlation coefficients for strength measurement reliability were 0.86, 0.73, and 0.72 for conditions A, B, and C, respectively.

3.3. Neck muscle Size-Strength relationships

The neck muscle size-strength relationships as characterized by the linear regression models are sex and posture dependent (Fig. 3 & Fig. 4). All relationships reported below were found to be significant with 0 falling within the relatively narrower 80% confidence intervals of regression model intercepts unless otherwise stated. In condition A, the sex-specific models showed significant correlations between total superficial flexor size (AS + SCM + IH) and strength (Fig. 3). There was no significant difference in regression slope between males and females, while the regression models for females had consistently lower R^2. At the individual muscle level, only the SCM was significantly correlated with strength. For males, this significance was consistent across all morphometric measures, which was not the case for females. The R^2 values for female SCM models were markedly lower than those of males. A significant relationship between IH volume and strength was found in females. In condition B, a significant relationship was found between AS size and exertion strength for males but not for females (Fig. 4). In condition C, no significant correlations were found for males; several significant correlations were identified for females but with 0 falling outside the 80% confidence interval for model intercepts.

Table 4
Comparison of correlations of strength in conditions A to strengths in non-neutral conditions. Pearson's *rho* (and *p*-values) are reported for males and females.

Condition	Male	Female
B	0.43 (0.147)	0.77 (<0.001*)
C	0.42 (0.148)	0.71 (0.001*)

4. Discussion

The growing concerns of neck pain and head injury have motivated biomechanical investigation of measures or modifiable factors pertinent to the causation and prevention of these injuries. Neck muscle strength and size have been identified as potential measures, but their interplay and relationships remain poorly understood, especially with regard to sex differences. This study examined muscle size-strength relationships across varied postures in order to identify potential sex differences, determine the roles of muscles or muscle groups in specific neck exertions, and compare three muscle size metrics.

The reliability of this study, in terms of strength measurement, MRI segmentation, and the size-strength relationships themselves, compares favorably with previous studies. As measured by ICCs, reliability of strength measurement ranged from good to excellent across the experimental conditions (Cicchetti, 1994; Hildenbrand and Vasavada, 2013). The present study showed an intra-observer variability of<5% for muscle volume measurement. No prior studies have reported reliability measures of manual muscle segmentation in the neck, but MRI segmentation variability of rotator cuff muscle volume was reported to be < 4% (Li et al., 2014; Tingart et al., 2003). As a whole, segmentation for muscle volume has been shown to have errors generally under 5%, calculated by water displacement (Audenaert et al., 2009; Lehtinen et al., 2003; Tingart et al., 2003). The reliability of the muscle size-strength relationships from linear regression can be interpreted from the y-intercepts of the models. A positive intercept for the linear relationship would imply force generation without muscle, signifying the potential for misleading results; more specifically, intercepts significantly deviating from 0 may indicate submaximal muscle activation or poor measurement of strength or muscle size (Bamman et al., 2000; Bruce et al., 1997). Hence, regression models correlating muscle size to strength are deemed unreliable when intercepts fail to meet this criterion. All significant relationships reported in this study exhibited intercepts not significantly different from 0, falling within the narrower 80% confidence intervals.

Sex differences in strength appear to result primarily from differences in muscle size, but differences in the predictability of this relationship point to more complex underlying reasons. In the subject population, the only significant anthropometric sex difference was height; nonetheless, males were significantly stronger than females, with ratios similar to those found in previous studies (Catenaccio et al., 2017; Hildenbrand and Vasavada, 2013). Models found no significant sex difference in model slopes, except for the AS in an extended posture. This supports the hypothesis that the difference in neck strength, at least in the neutral posture, can be attributed to muscle size. In other words, there is no sex-specific effect granting male muscle more strength. However, while there was no clear difference between slopes of the relationships, a greater percentage of strength variability was left unexplained by muscle size in females, as all male muscle size-strength relationships yielded higher R^2 values. One explanation could be the greater variation of muscle morphometry, specifically muscle moment

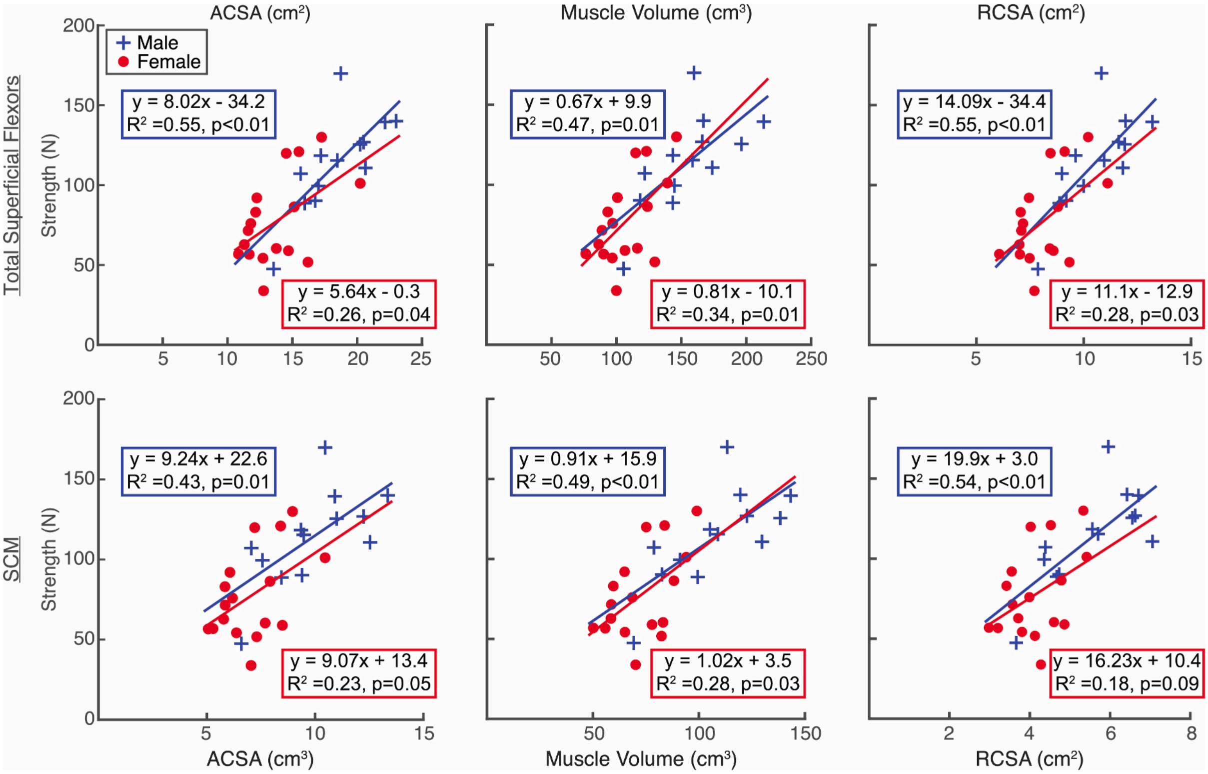


Fig. 3. Sex-specific neck muscle size-strength relationships in condition A identified by linear regression for the total superficial flexor (AS + SCM + IH) and SCM alone, comparing three morphometric measures (ACSA, MV, and RCSA).

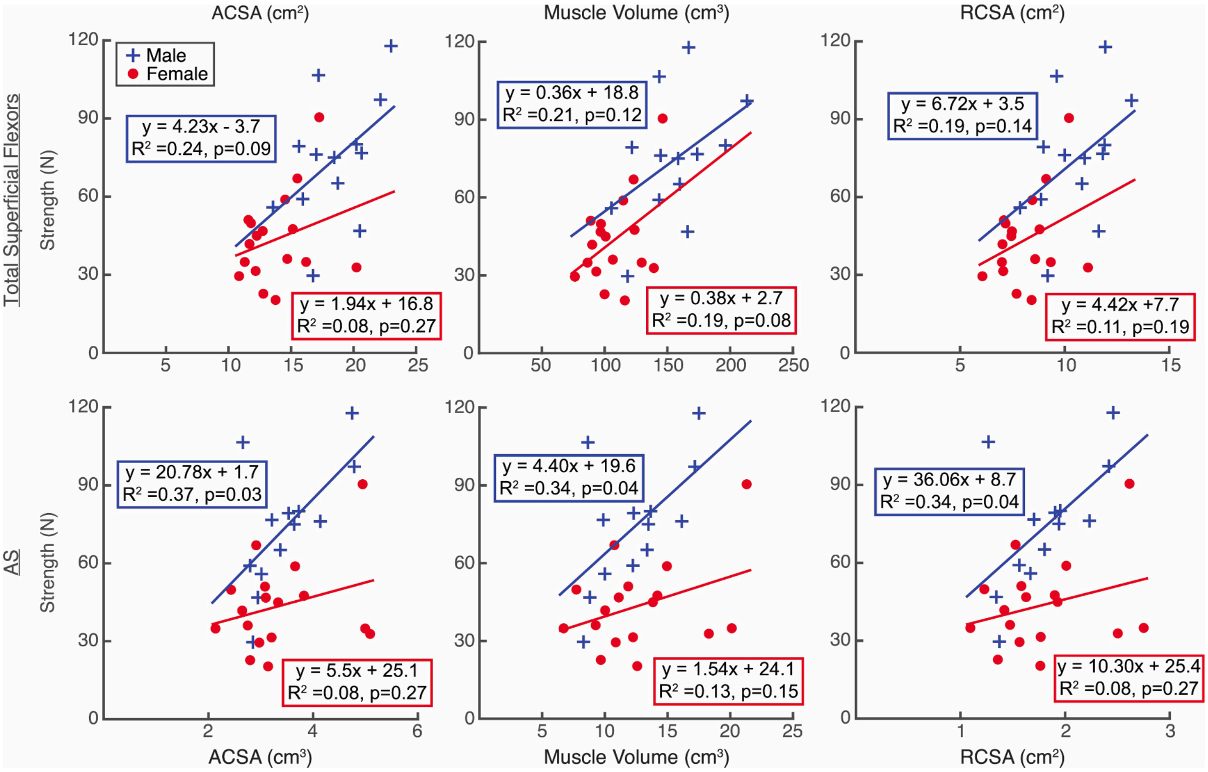


Fig. 4. Sex-specific neck muscle size-strength relationships in condition B identified by linear regression for the total superficial flexor (AS + SCM + IH) and AS alone, comparing three morphometric measures (ACSA, MV, and RCSA).

arms, in females compared to males. However, this does not explain why females exhibited significant inter-posture strength correlations while males did not. For females, strength in condition C was a strong predictor of strength in condition A in spite of the fact that the exertions are in opposite directions involving antagonistic muscles. Thus, there appears to be some set of qualities, apart from muscle size or morphometry, endowing greater strength to some females but not others. Though fiber type composition of neck muscle may vary between subjects, it has been shown to have little effect on muscle specific tension (Miller et al., 1993). A larger difference in activation of agonists and antagonists between strong and weak females could explain this phenomenon (Dal Maso et al., 2012). An investigation of this hypotheses would require integrating subject-specific muscle morphometry and electromyographic (EMG) data with the muscle size and strength measurement techniques used in this study. Given the observed sex differences and disparities in prevalence and treatment outcomes, future research into neck strengthening intervention is warranted and should analyze males and females separately.

Though weak in females, muscle size-strength relationships were strong in males and provided evidence for the contribution of specific muscles to the neck exertions studied. The *r* of 0.74 for total superficial flexor RCSA to neutral flexion force is comparable to muscle size-strength relationships in other joints including the shoulder, elbow, and wrist (Akagi et al., 2009; Bamman et al., 2000; Fukunaga et al., 2001; Holzbaur et al., 2007a; Miller et al., 1993). The SCM is widely regarded as the primary flexor of the neck and has been the focal muscle for sport-related perturbation studies (Ackland et al., 2011; Alsalaheen et al., 2018; Schmidt et al., 2014). Our results show that SCM size variation accounts for 44% of neutral flexion strength variation in males, and the *r* of 0.73 is similar to the relationships reported for elbow flexors and extensors (Akagi et al., 2009; Fukunaga et al., 2001). Because the SCM has been shown to generate an extension moment about C7, we hypothesized that the other anterior neck muscles (Longus, IH, or AS) would show stronger relationships with strength in condition B (Vasavada et al., 1998). Longus size has been linked to chronic neck pain; however, its short moment arm prevents large joint torque generation (Amiri Arimi et al., 2018). The IH contribution to flexion has been shown *in silico* using musculoskeletal modeling software, OpenSim (Mortensen et al., 2018). The IH muscles contribute to head-neck flexion by indirectly creating downward force on the mandible. The lack of direct force to the mandible, through a chin strap akin to a football helmet, may explain why a significant IH size-strength relationship was largely not observed in our study (except MV-strength correlation in females). Therefore, it was not surprising to find that the AS had the strongest relationship with neck flexion strength in condition B. Given that this exertion is commonplace in sports where an anterior torso lean and an upright head are common, quantification of AS size in neck strengthening studies for injury risk may be beneficial. The development of strength intervention strategies should consider a full range of positions to account for weak inter-position strength correlation and differing muscle involvement. Further research to identify neck extensor size-strength relationships is warranted.

No significant difference was observed among the three muscle morphometric measures for depicting size-strength relationships. For other muscles and joints, MV and ACSA have been compared with mixed results (Akagi et al., 2009; Fukunaga et al., 2001). In the present study, RSCA-based relationships had intercepts closer to 0 and MV models were slightly stronger. For the purpose of neck strength correlation analysis, there appears to be no obvious disadvantage to use ACSA in terms of accuracy and sensitivity. For more clinically oriented studies where efficiency, cost-effectiveness, and portability may take priority, ultrasonographic measurement of ACSA would be recommended for data acquisition.

Several limitations of this study are noted to inform future investigations. Nine participants' data were excluded due to image blur caused by excessive motion artifact in MRI scans. Muscle segmentation was performed manually slice-by-slice, a time-consuming process that limited the number of replicates used for reliability analysis. Static strength was measured in the present study given the equipment constraint and interest in statically held deviated postures. Dynamic strength data may be more pertinent to acute head or neck injury prevention applications.

In conclusion, the findings from the current study of neck muscle size-strength relationship highlight the importance of sex differences and testing a full range of motion for clearer understanding of the relationship and development of strength-based injury prevention strategies.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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