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Developmental biomechanics of neck musculature

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Abstract

Neck mechanics is central to head injury prevention since it is the musculoskeletal neck, which dictates the position and movement of the head. In the US, traumatic injury is the leading cause of death for children; however prevention is hampered by the lack of data concerning the mechanics of the immature head-and-neck. Thus, the objective of this study was to quantify neck muscle strength and endurance across the maturation spectrum and correlate these with head-and-neck anthropometry. A factorial study was performed on 91 human subjects measuring head-and-neck anthropometry and neck strength and endurance in three bending directions (flexion, extension, and lateral) as a function of age (6–23 years). Using a custom device, neck maximum voluntary contraction (MVC) force was measured in triplicate. Next, neck muscle endurance (sustained effort) was measured as the subjects' ability to maintain 70% of peak force over 30 s. Linear regression of peak force and endurance as a function of age revealed each direction to significantly ($p < 0.0001$) increase with age. The MVC force, averaged across all directions and normalized to the adult values, exhibits the following maturation curve: %MVC Force = $-0.0879(\text{age})^2 + 6.018(\text{age}) + 8.120$. Neck muscle strength, similar between young males and females, becomes disparate in adolescence and adulthood with males exhibiting greater strength. Bending direction differences were also found with extension strength being the greatest regardless of age and sex. Furthermore, neck circumference appears predictive of neck strength and endurance in children. Together, these relationships may facilitate improved design of injury prevention interventions.

Keywords

Biomechanics; Cervical spine; Neck muscle strength; Children

1. Introduction

In the US, traumatic injury is the leading cause of death for children under the age of 24 years (15,000 each year) (NCSA, 2003). Specifically, head and neck trauma comprise the majority (>80%) of these child fatalities and further leave thousands of children with life-long debilitation consequences (Conn et al., 2006; Osenbach and Menezes, 1992;

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Conflict of interest statement

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vanRooyen et al., 1995). These injuries are the result of motor vehicle crashes, sport accidents, and falls—many of which have the potential to be prevented. In 2004 there were approximately 40,000 children injured under the age of 16 as a result of motorized sports vehicles (Gaines et al., 2004). While head and neck injuries are often grouped, neck injuries alone have been shown to account for the single most frequent injury (rate of 870 per 100,000 per year) of motor vehicle occupants under the age of 19 treated in emergency departments (Quinlan et al., 2004; Versteegen et al., 2000). Additionally, bicycle-related head injuries account for 400 fatalities and 480,000 emergency department visits annually (Bijur et al., 1995; Committee on Injury and Poison Prevention, 2001).

In an effort to ameliorate child safety, helmets and safety systems have been developed to mechanically protect the maturing head and neck. Helmet design aims to protect the skull and brain during an impact and also minimize fatigue and injury to the neck (Friede et al., 1985). Child helmet design has utilized data collected on head dimensions throughout growth and maturation; (Bradtmiller and Shirley, 1995) however, head-to-body allometric relationships throughout development change significantly, where head mass and dimensions may not predict neck muscle ability. The child's head circumference reaches approximately 90% of its adult size by age 4 whereas the neck circumference approaches 90% adult at age 14 (Arbogast et al., 2003). Since it is the musculoskeletal neck, which dictates the position and motion of the head, it is essential that we understand the biomechanics of this system in order to better prevent neck and head injuries.

Studies have recently identified growth curves, which describe developmental patterns and biomechanical properties for the immature-to-adult head and cervical spine. Head geometrical (Bradtmiller and Shirley, 1995) and biomechanical (Arbogast et al., 2003; Cheng and Reichert, 1998; Margulies and Thibault, 2000; Wang et al., 2001) changes have been measured throughout maturation revealing differential patterns suggesting the child head is not simply a scale down of the adult (Farkas and Posnick, 1992). Similarly, cervical spinal column development involves a complex sequence of ossification and matrix reorganization creating distinct morphology (Canale, 1998; Kuhns, 1998; Ogden, 1984a,b) and biomechanics (Arbogast et al., 2007; Ching et al., 2001; Nuckley and Ching, 2006; Nuckley et al., 2004; Nuckley et al., 2002; Pintar et al., 2000; Urban and Roberts, 1995). These age-related changes in cervical spine mechanics describe the path of spinal motion and positioning of the head; however, it is the neck muscular mechanics which drives the movement, positioning, and subsequent risk of injury to the head.

Neck movement is dictated by the sternocleidomastoid, longus colli, and longus capitis for flexion, a concerted effort of the splenius capitis, semispinalis, suboccipitals, and trapezius for extension, and the scalenes, sternocleidomastoid, and fibers from the trapezius to control lateral bending (Jenkins, 2002). Many studies have measured isometric neck mechanics, (Alicsson et al., 2001; Ashton-Miller et al., 1990; Conley et al., 1997; Garcés et al., 2002; Jordan et al., 1999; O'Leary et al., 2005; Staudte and Duhr, 1994; Suryanarayana and Kumar, 2005; Vasavada et al., 2008; Vasavada et al., 2001) isotonic mechanics, (Ono and Kanno, 1996) and isokinetic mechanics (Hong et al., 2005; Portero et al., 2001; Seng et al., 2002) as well as correlating electromyography to identify adult neck muscle activation (Gabriel et al., 2004; Kumar et al., 2005; Kumar et al., 2003; Strimpakos et al., 2005; Tierney et al., 2005; Valkeinen et al., 2002; Vasavada et al., 2002). Adult neck muscle mechanics has been measured identifying directional maximal forces and moments generated by the neck (Chiu et al., 2002; Jaric, 2002; Kumar et al., 2001, 2003; Seng et al., 2002; Suryanarayana and Kumar, 2005; Valkeinen et al., 2002; Vasavada et al., 2001) as well as endurance characteristics (Gosselin et al., 2004; Harris et al., 2005; Lee et al., 2005; Schieppati et al., 2003; Schulte et al., 2006).

Several studies have investigated pediatric muscle mechanics; however, they have been limited to examining the strength of the extremities and torso (De Ste Croix et al., 2003; Neu et al., 2002; Rauch et al., 2004). To our knowledge, no studies have investigated neck muscle mechanics throughout development, but these previous studies, identifying increasing strength with maturation, portend similar neck muscle strength maturation patterns.

The goal of this study was to quantitatively measure the developmental biomechanics of the musculoskeletal neck and determine neck muscle strength and endurance growth curves. The following scientific hypotheses motivated this research effort: (i) Neck muscle strength increases with advancing maturity (age) to adulthood, (ii) Neck muscle endurance increases with advancing development, and (iii) The differential strength patterns with respect to loading direction in adults are also exhibited in the pediatric populace. To test the stated hypotheses, we performed a human subject research project which examined children of different ages (independent variable) for their neck strength and endurance (dependent variables) in a factorial study design.

2. Methodology

A field study on pediatric human subjects was performed to define the relationships between neck anthropometry, neck maximal voluntary contraction (MVC) force, and neck endurance or sustained effort in a maturing population (6–23 years). This methodology received approval by the University of Washington Human Subjects Review Committee (05-5292-E/C-01) and meets all IRB requirements.

The sample size targeted 30 individuals within each of three age groups (6–11, 12–17, and 18–23) with equal sex distribution. The subjects were recruited from local Seattle Public Schools and the University of Washington.

2.1. Neck muscle mechanics measurement device

Isometric neck muscle strength and sustained effort were measured using a custom apparatus designed to isolate and measure the forces exerted by each subject's neck muscles. A head device attached to a chair enabled each seated subject to apply neck muscle contraction forces via their head to the apparatus whereby neck muscle mechanics were measured in the upright neutral posture (Fig. 1). Active insufficiency of torso contributors was accomplished by placing each subject in the seated position with their feet on a stool legs extended. This apparatus and posture facilitated neck muscle force measurement as applied through the head, while trunk muscle activation provided torso stabilization only. A six-axis load cell (Model 4386, Robert A. Denton, Inc., Rochester Hills, MI) attached to the head device measured the forces and moments in flexion, extension, and lateral bending. The data were acquired using a custom LabVIEW (National Instruments Corp., Austin, TX) virtual instrument on an NI-DAQ USB device (USB-6009, National Instruments Corp., Austin, TX) with 16-bit resolution on a laptop computer.

2.2. Experimental protocol

Following both written and oral consent for participation, each subject's height (cm) and weight (kg) were measured. Head and neck dimensions were measured using a cloth tape measure (accuracy ± 1.7 mm) and calipers (accuracy ± 1.4 mm). Head measurements were made according to the work by Bradtmiller and Shirley (1995) including head circumference, breadth, and height. Neck circumference was measured in neutral position at the midway point between the chin and the base of the neck (Fig. 2). Neck length was defined as the distance from the C7 spinous process to the tragus.

Mechanical testing was demonstrated by the researcher for each subject and they were given opportunity to stretch their neck muscles prior to testing. Each subject was seated in the neck-muscle-mechanics-measurement device in an upright neutral posture with their legs extended and resting on a footstool. The head device was lowered around their head to ½ cm above their eyebrow and they were instructed to lightly push with their head in each direction (flexion, extension, and laterally) to familiarize themselves with the procedure. Along with physical neck muscle isolation via the apparatus, each subject was instructed to focus on specific motions; for example, flexion was described as a yes-nodding movement (Fig. 2). Once comfortable, each subject performed an MVC push in each direction in triplicate (randomized order). Subjects were instructed to ramp up and push as hard as they could for 3 s. The data were collected at 40 Hz over 10 s. Between trials, a 1 min rest period was given and the subjects were reminded of their posture.

Following the MVC muscle force experiment, the endurance or sustained effort of each subject's neck muscles was investigated. Sustained effort was defined as the area under the force time history for a sustained push of 30 s. Subjects were asked to apply and maintain 70% of their previous maximal force (maximum from the three trials) for 30 s. Throughout the duration of this test, subjects were reminded to breathe, but not coached verbal or non-verbal. Force data were collected at 40 Hz for 30 s. This test was conducted once for each direction in a randomized order with an opportunity to rest between tests.

2.3. Data analysis

The raw force and moment data were initially transformed to the forces applied at each pad for both the MVC and endurance experiments. The MVC force data were filtered using a low-pass Butterworth filter with a 0.8 Hz cut-off frequency. The peak value of the three trials was then recorded as the MVC force in each direction. Sustained effort data were filtered using a low-pass Butterworth filter (0.5 Hz cut-off frequency) and the area under this force time history curve was calculated via trapezoidal numeric integration.

Subject anthropometry, MVC force, and sustained effort data were then evaluated with regard to subject age to test the stated hypotheses. A linear regression *F*-test was used to examine the relationships between maturation (age) and MVC force and sustained effort (hypotheses i and ii). These analyses were performed with blocking by bending direction, blocking by sex, and grouped together. The third hypothesis was tested using analysis of variance (ANOVA) techniques comparing strength by direction within each age group. Post-hoc *F*-tests were used to examine the relationship between anthropomorphic measurements and neck strength and endurance. Further post-hoc comparisons were made using ANOVA techniques with Tukey HSD contrasts comparing strength by direction, sex, and age group. The main effects (hypotheses) statistical comparisons were examined for an alpha acceptance of 0.05 and the Bonferroni correction was applied to the post-hoc comparisons such that alpha was 0.005.

3. Results

The 91 subjects between the ages of 6 and 23 years were distributed throughout the height and weight average growth charts for children (CDC) and no child fell outside the 5th-to-95th percentile body mass index (BMI) (Fig. 3)(CDC Growth Charts: United States, 2000). Subject enrollment included 17 male and 14 female 6–11 year olds, 14 male and 14 female 12–17 year olds, and 17 male and 15 female 18–23 year olds. The head circumference data collected herein overlaid metrics in the literature of average head circumference throughout maturation suggesting a population representative sample (Bradtmiller and Shirley, 1995).

The MVC force data was modeled similar to other human ontogenetic growth trajectories using a second order polynomial by age demonstrating increasing force generation with advancing maturity (Fig. 5). Neck flexion, extension, and lateral bending demonstrated statistically increasing force production with age ($p<0.0001$) while exhibiting sex differences.

Grouping the MVC force data by age groups enables a specific investigation into the differences between the sexes and directions of bending based on the pre-pubescent child, the pubescent adolescent, and the adult. Fig. 4 illustrates the average MVC force for each age group divided by sex and direction of bending. Extension bending was statistically larger than the other directions ($p<0.0001$) using an ANOVA Tukey HSD contrast. Further ANOVA post-hoc contrasts revealed no sex differences in the young age group. Sex differences for the middle age group (12–17 years) were found to be statistically distinct in extension ($p=0.005$) and different, although not statistically unique, in flexion ($p=0.05$). The adult age group (18–23 years) demonstrated statistically different forces for each direction of bending with regard to the sexes: flexion ($p=0.001$), extension ($p=0.0001$), and lateral bending ($p=0.004$).

Neck flexion, extension, and lateral bending sustained effort were found to statistically increase with advancing age (F -test, $p<0.0001$) (Fig. 5). These sustained efforts also exhibited differences between the sexes.

The test sample anthropometry is presented by age in Table 1. Neck circumference significantly advanced with maturation ($p<0.0001$). The normalized neck circumference followed a second order polynomial ($r^2=0.5406$) such that Percent Adult Neck Circumference= $-0.0819(\text{age})^2+4.00(\text{age})+52.42$ where the measured average adult neck circumference was 34.97 cm (SD=11.04 cm). Neck MVC force and sustained effort (average of the three directions) were regressed by neck circumference and revealed significantly escalating values with increasing neck circumference ($p<0.0001$) (Fig. 6).

4. Discussion

Neck muscle maximum voluntary contraction force significantly increased with advancing maturity, leading us to reject null hypothesis (i). Null hypothesis (ii) stating that endurance of the cervical musculature would not be correlated with maturation was also statistically rejected. Finally, because the differential strength patterns between flexion, extension, and lateral bending observed in adults follows the same pattern in children; null hypothesis (iii) is rejected. In sum, each null hypothesis is rejected leaving the alternative hypotheses as plausible means of explaining the developmental course of the musculoskeletal neck biomechanics.

The modeling of this system facilitates the development and examination of injury prevention systems and products tuned (biomechanically appropriate) for children. The mean MVC force data in all directions were fit with a 2nd order polynomial and then normalized to the adult (18–23 year old) mean value. This relationship, modeling the MVC force as a function of age, provides a percentile based assessment of neck muscle strength which can be compared with other metrics (Fig. 7). For example, an 8 year old's head circumference was measured in our study to be 91% of its adult size while concurrently, the MVC force of the neck musculature supporting the head is only 50% of its adult value. This mismatch may implicate the inability of neck musculature to adequately move the head out of harm's way leading to injuries in this populace. Compared with other developmental muscle strength data, these curves have similar shapes and sex distinctions (Carron and Bailey, 1974; De Ste Croix et al., 2003; Lefkoff, 1986; Neu et al., 2002). Specifically, at 8 years of age, forearm grip strength and quadriceps strength have been measured to be 38%

and 45% of adult values respectively (De Ste Croix et al., 2003; Neu et al., 2002). The sustained effort data were modeled in a similar fashion as a function of age (Fig. 8).

The protective ability of neck musculature in adults has been demonstrated to significantly affect the level of injury and the forces required for osteoligamentous injury due to tensile loading mechanisms (van Ee et al., 2000). It has been suggested that children (<8 years) are prone to high cervical spine injuries because of the relatively large head, high axis-of-rotation, and weak neck musculature (Brown et al., 2001; Eleraky et al., 2000; Finch and Barnes, 1998; Hadley, 2002; Kokoska et al., 2001; McCall et al., 2006). The data herein quantitatively demonstrate the diminished relative capacity of the child neck musculature whereby supporting these claims.

Neck strength and endurance were found to differ between males and females (Figs. 4–6). While young children exhibited no differences, the middle age group demonstrated some significant differences between the sexes and adults display distinct male and female neck MVC forces for all directions. The middle (adolescent) age group appears to be a transitional region where hormonally driven changes lead to rapid and different muscle development between the sexes (Ioakimidis et al., 2004; Martini et al., 2003; Neu et al., 2002; Schonau, 1998). Males and females mature at different rates for different tissues leading to altered body proportions (Ioakimidis et al., 2004; Schonau, 1998).

Neck circumference exhibited a statistically significant correlation with both MVC force and sustained effort (Fig. 6). Previous studies on adults have not found neck circumference to be correlated with biomechanical metrics (Jordan et al., 1999; Kumar et al., 2001; Suryanarayana and Kumar, 2005; Vasavada et al., 2001). Our maturing population, all containing healthy BMI values (not obese), likely represents a different population from those previously tested.

Comparison of our adult data with the literature reveals our neck strength results to be similar in magnitude as well as directional and sex-based trends (Table 2). Adult MVC force data compare well with the literature in spite of their different testing protocols (Chiu et al., 2002; Kumar et al., 2001; Suryanarayana and Kumar, 2005; Valkeinen et al., 2002). Vasavada et al. (2001) recorded the moments about the C7-T1 vertebral level for adults. Comparison of the approximate moments (computed using neck anthropometry) produced in the study herein yield slightly lower moment values than Vasavada's (<28%), but with similar sex and directional relationships. These adult comparisons provide confidence in our methodology and support the subsequent examination of child (6–17 years old) neck muscle strength.

This study was the first to measure pediatric human subject neck muscle mechanics and thus, by its nature has several limitations which contextualize the results. The procedures were explained with age appropriate language; however continuous verbal or visual stimulation was not provided in an effort to standardize subject interfacing. The lack of feedback for the target load in the endurance test also presents limitations; results may indicate fatigue coupled with drift due to a lack of continuous feedback (Iridiastadi and Nussbaum, 2006). Previous methodologies have incorporated a shoulder restraint system in an attempt to isolate the cervical spine (Chiu et al., 2002; Kumar et al., 2001; Suryanarayana and Kumar, 2005; Valkeinen et al., 2002; Vasavada et al., 2001). Since our study involved only the upright neutral position without bending, the recruitment of other muscles during the test was unlikely. Further, our posture (legs extended, hands folded in lap, upright tall spinal posture) coupled with the verbal directions created a test sample, which did not move in the chair. Thus, our test apparatus required torso stabilization without leverage points

(restraints) whereby isolating the neck muscles and producing similar results to studies incorporating restraint systems.

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Fig. 1. Neck muscle mechanics measurement device. Photographs of the entire apparatus (A) including the chair with head device (B) containing a 6-axis load cell capable of measuring applied forces (C) in flexion, extension, and lateral bending.

Fig. 2. Experimental measurements. Most measurements made were similar to previous work (Bradt Miller and Shirley, 1995; Chiu et al., 2002; Kumar et al., 2001; Suryanarayana and Kumar, 2005; Valkeinen et al., 2002; Vasavada et al., 2001) including standard anthropometrical measurements (A) and adding neck circumference measurement (B) to complement the neck mechanics measurements (6-y.o. M).

Fig. 3. Body mass index of sample. The male (A) and female (B) body mass index (BMI) values (weight/height²) from the current study are overlaid upon the 5th-to-95th percentile BMI values as reported by the CDC Growth Charts: United States (2000).

Fig. 4.

Average MVC force grouped by age, sex, and bending direction. This plot demonstrates age group differences in neck muscle force production as well as sex differences (solid=male, striped=female), and differences between bending directions. Extension direction in each group is statistically (§ $p < 0.0001$) larger than flexion and lateral bending. Sex differences are observed within an age group and bending direction for the older age groups (^o $p = 0.05$; * $p < 0.005$).

Fig. 5.

Maximal voluntary contraction force as a function of age. These plots demonstrate the maturation and sex differences in neck strength for flexion (A), extension (B), and lateral bending (C). Second order polynomial curve fits describe all of the data (male and female combined). Sustained effort as a function of age. These plots demonstrate the maturation and sex differences in neck endurance for flexion (D), extension (E), and lateral bending (F). The combined male and female data were fit with a second order polynomial to describe the maturation patterns.

Fig. 6.

Maximal voluntary contraction force and sustained effort as function of neck circumference. A linear relationship describes the predictive ability of neck circumference such that 61% of the MVC Force variance is explained by neck circumference and 58% of the variance in sustained effort is described by neck circumference.

Fig. 7.

Model of percent neck muscle MVC force as a function of age. All of the MVC Force data were normalized to the adult (18–23 y.o.) mean and then fit with a 2nd order polynomial. This mean and standard deviation plot demonstrates the maturation of neck strength and is juxtaposed with head circumference data for comparison. Note that an 8 year old has an average head circumference of 91% adult while its neck strength is merely 50% of adult.

Fig. 8.

Model of sustained effort as a function of age. Sustained effort data in all directions and for both sexes were included and normalized to the adult (18–23 y.o.) mean value and fit with a 2nd order polynomial describing the growth trajectory of neck endurance as a percent of adult. These data are contrasted with the head circumference data collected herein at various ages.

Table 1

Test sample anthropometric data.

Age	Males					Females										
	N	Height (cm)	Weight (kg)	Head Cir (cm)	Neck Cir (cm)	Head B (cm)	Head L (cm)	Neck L (cm)	N	Height (cm)	Weight (kg)	Head Cir (cm)	Neck Cir (cm)	Head B (cm)	Head L (cm)	Neck L (cm)
6–7	6	120.5	23.1	52.7	27.0	14.6	13.8	6.4	2	127.8	25.6	54.2	26.4	14.2	12.7	8.2
8–9	5	141.2	35.8	54.6	29.0	14.9	13.8	8.8	7	137.1	29.1	54.0	27.0	14.4	12.7	9.1
10–11	6	148.5	42.3	54.6	29.7	14.6	14.3	9.7	5	152.3	46.9	55.2	29.2	14.7	13.3	8.9
12–13	4	158.1	52.2	56.1	32.3	15.1	14.1	9.5	4	156.6	52.0	56.3	30.9	14.9	12.7	9.3
14–15	7	172.7	61.2	57.3	33.8	15.4	14.3	9.0	5	164.6	65.3	56.0	32.7	14.8	13.5	8.7
16–17	3	178.0	67.7	58.9	35.9	15.2	13.6	10.5	5	158.9	57.5	56.7	31.6	14.8	13.5	7.8
18–19	6	174.3	74.4	58.6	37.2	15.6	14.2	9.8	6	161.0	64.3	56.1	32.4	14.9	13.0	8.9
20–21	5	177.6	78.2	58.5	38.3	15.1	14.2	9.9	5	161.5	54.2	55.1	30.7	14.7	13.4	8.4
22–23	6	186.2	83.4	58.1	37.7	15.4	14.8	10.6	4	163.5	62.5	56.4	32.1	15.4	14.1	7.4

Table 2

Maximal voluntary contraction force (N) as measured in adults: a literature comparison.

	Males			Females		
	Flexion	Extension	Lateral	Flexion	Extension	Lateral
Present study	$N=17$ (18–23 yrs)	90.3 (34.2)	167.3 (66.1)	70.6 (19.3)	$N=15$ (18–23 yrs)	38.1 (11.2)
Chiu et al. (2002)	$N=17$ (20–39 yrs)	90.6 (35.9)	96.2 (48.4)	63.7 (25.8)	$N=17$ (19–39 yrs)	68.6 (19.9)
Kumar et al. (2001)	$N=21$ (19–29 yrs)	72.0 (18.0)	100.0 (28.0)	76.0 (23.0)	$N=19$ (20–29 yrs)	41.0 (14.0)
Suryanarayana et al. (2005)	$N=19$ (18–30 yrs)	31.4 (9.9)	45.1 (24.3)		$N=20$ (18–30 yrs)	19.8 (10.2)
Valkeinen et al. (2002)	$N=29$ (18–55 yrs)	151.0 (47.0)	278.0 (50.0)		$N=28$ (18–55 yrs)	75.0 (21.0)
						170.0 (28.0)