

COMPARISON OF PASSIVE CERVICAL SPINE FLEXION IN CHILDREN AND ADULTS

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ABSTRACT

Head trauma is the most frequent injury sustained by children in car crashes, and the neck plays a key role in governing head kinematics during the crash. Pediatric anthropomorphic test devices (ATDs) are used to assess the risk of head injury, yet the pediatric ATD neck is a size-scaled model of the adult ATD neck, with no consideration for the tissue properties and morphological changes during human development. To help understand the effects of maturation on the changes in neck flexion biomechanics, this study compared the passive cervical spine flexion of children to adults in specific age groups (6-8, 9-12, 20-29, 30-40 years). Subjects with restrained torsos and lower extremities were exposed to a 1g inertial load in the posterior-to-anterior direction, such that the head-neck complex flexed when the subject relaxed their neck musculature. Surface electromyography with audio feedback was used to coach the subjects to relax their neck musculature. A multicamera 3-D target tracking system was employed to capture the motion of specific landmarks on the head (Frankfort Plane) and thoracic spine (T1 and T4). Neck flexion angle with muscles relaxed was calculated for each subject. Neck flexion angle significantly decreased with age, with changes in head-to-neck girth ratio partially explaining the decrease. A statistically significant increase in cervical spine flexion was found in adult females compared to adult males. Data also illustrate this trend in children, but it was not statistically significant. In summary, these results demonstrate an increased passive cervical spine flexion in children compared to adults, and females compared to males.

These data will help guide the development and validation of pediatric ATDs.

INTRODUCTION

Head trauma is the most frequent injury sustained by children in car crashes (Durbin et al., 2003) and the neck plays a key role in governing head kinematics during the crash. Designing effective motor vehicle safety systems to mitigate such injuries requires the use of a humanlike (biofidelic) anthropomorphic test device (ATD). In the case of head injury assessment, it is essential that the ATD accurately predict the likelihood of an interior head impact and, given an impact, the velocity and orientation of the head immediately prior to impact.

The ATD neck is of particular importance when predicting head kinematics as it is the primary structure through which restraint loads are transferred from the torso to the head. The biofidelity requirement for the adult ATD neck is specified as a relationship between the bending moment at the head/neck junction and the angle between the head and the torso (Mertz et al., 1989). This relationship has been quantified for adults via experimental studies of the cervical spine in post-mortem human subjects (PMHS), post-mortem animal subjects (PMAS), and live human volunteers (Mertz and Patrick, 1967; Mertz and Patrick, 1971; Ewing and Thomas, 1973; Mertz and Patrick, 1973; Melvin et al., 1973; Ewing et al., 1975; Ewing et al., 1976; Patrick and Chou, 1976; Ewing et al., 1977; Ewing et al., 1978; Begeman et al., 1983; Wismans and Spenny, 1984; Wismans et al., 1986; Ma et al., 1995;

Thunnissen et al., 1995; Deng et al., 1998, Ching et al., 2001; Hilker et al., 2002; Nightingale et al., 2002; Nuckley and Ching, 2006; Nightingale et al., 2007). However, owing to the paucity of pediatric cadaver biomechanical data, the 3 and 6 year old pediatric ATD necks have been based on size-scaled models of adult data with little consideration for the tissue and morphological changes during human development (Irwin and Mertz, 1997).

A growing body of literature suggests that, biomechanically, children are not simply size-scaled versions of adults. From year 1 to 2, C1 consists of three bony masses that fuse to form the ring structure of C1 at age 4 to 6 years. Similarly, at birth C2 is comprised of 4 pieces, and fuses completely by age 6 years. Vertebrae C3 through C7 are each represented by 3 separate bony masses at birth, which fuse by age 4 years. The uncovertebral joints present in C3-C7 do not form until age 6 years (Schuer and Black, 2000). In the child, the ligaments are lax as compared to the adult, and the facets are predominantly horizontal, thus providing limited restriction of anterior-posterior shear (subluxation) at the facets (Bailey, 1952; Townsend and Rowe, 1952; Sullivan et al., 1958; Cattell and Filtzer, 1965; Kewalramani and Tori, 1980; Walsh et al., 1983; Menezes, 1987; Hadley et al., 1988; Pollack et al., 1988; Fuchs et al., 1989; Osenbach and Menezes, 1989; Janssen et al., 1991; Kriss and Kriss, 1996; Schuer and Black, 2000; Weber, 2002; Yoganandan et al., 2002). The current pediatric neck scaling procedures (Irwin and Mertz, 1997) do not consider age-dependent differences beyond size. Consequently, the biofidelity of current pediatric ATD necks are called into question.

Recent studies have examined the differences in biomechanical response of the cervical spine across the age range using PMHS, PMAS and human volunteers. Using a baboon model, Ching et al. (2001) measured the tensile stiffness of different functional spinal units (FSU). The results illustrated an average 75% increase in tensile stiffness of the C7-T1 FSU compared to the Oc-C2 FSU in 3 year old specimens, versus a 6% decrease in 12 year old specimens. A second baboon model by Nuckley and Ching (2006) showed a significant correlation between maturation and increasing tensile and compressive stiffness of the cervical spine. Hilker et al. (2002) demonstrated that the bending stiffness of 6 and 12 year old human age-equivalent caprine specimens were 40% and 60% of adult caprine specimens, respectively. Increased tensile stiffness with age has also been demonstrated in pediatric PMHS tests. Nuckley et al. (2005) found increased

compressive stiffness at the C3-C5 joint while assessing 11 PMHS spines from 2 to 28 years of age. Similarly, Ouyang et al. (2005) examined 10 pediatric PMHS head-neck complexes with intact ligamentous cervical spines and found a 46% increase in tensile failure in older pediatric subjects (6-12 years) versus younger subjects (2-4 years).

Perhaps most relevant to the current study, Arbogast et al. (2007) measured the active cervical spine range of motion in 67 pediatric volunteers from ages 3 to 12 years. In this study, subjects with restrained torsos were asked to flex, extend, laterally bend, and rotate to their maximum range under active muscle control. The study concluded that, in children 3-12 years, active cervical spine flexion and horizontal rotation increased with age. Overall flexion in children was found to be greater than adults. This previous study characterized the active range of motion which is governed in part by forces generating by active firing of the muscles. As a complement to this work, we sought to characterize cervical flexion under *passive* muscle forces in pediatric and adult volunteers. Based on previous literature, we hypothesized that passive cervical spine flexion of pediatric volunteers will be greater than that of adults.

METHODS

Participants

Children 6-12 years and adults 20-40 years were enrolled into one of four age groups (6-8, 9-12, 20-29, and 30-40 years). Subjects were prescreened for prior injuries, physical limitations, or medical conditions involving the head, neck, or spine and to ensure their body mass index (BMI) fell within the 10th to 90th percentile.

Anthropomorphic Data

Subjects' height and weight were measured prior to setup and their BMI was calculated. The following anthropometric data were gathered using a flexible tape ruler: head girth, neck height (opisthocranium to C7), neck girth, seated height, and sternum height (distance from Xyphoid Process to the Manubrium).

Instrumentation

Subjects were asked to remove their shirt(s) and don a tight fitting, sleeveless shirt with cutouts along the thoracic spine and on the shoulders to accommodate photoreflexive markers and EMG electrodes on the skin. Prior to electrode placement, each subject's

skin was cleaned by applying NUPREP Skin Prepping Gel (Weaver and Co., Aurora, CO). Disposable, self-adhesive dual surface electrodes (Noraxon, Inc., Scottsdale, AZ) were placed bilaterally on the sternocleidomastoid (SCM), paraspinous (PS), and trapezius (TR) muscles (See Figure 1). A grounding electrode was centered over the left mastoidale. Electrodes were connected to the TeleMyo 2400T V2 telemetry system (Noraxon, Inc., Scottsdale, AZ) and electromyography (EMG) data were recorded throughout each trial at 1000 Hz per channel.

To collect our primary data measure, cervical spine flexion, the Eagle 1 Digital RealTime motion capture system (Motion Analysis, Inc., Santa Rosa, CA) was used. The Eagle 1 system consists of 8 cameras capable of tracking photoreflective markers in 3D space. To detect movement of the head, spine, torso and testing apparatus, 10mm diameter reflective markers were placed in the following locations (See Figure 2):

- Acromion Processes
- External Auditory Meatus (1.5 cm anterior)
- Head (on cap) front, left, right, top
- Midpoint between Xyphoid Process and Supra Sternal Notch
- Nasion
- Seatback top and bottom
- Sternoclavicular joints (~3 mm lateral to the sternoclavicular joint)
- T1
- T4

Motion analysis data were collected for each trial at a sampling rate of 60 Hz.

After EMG and motion analysis setup was complete, subjects were escorted to the testing apparatus. (See Figure 3) The device consisted of a rigid seatback, four point belt system, and thigh and lower leg restraints. The seat was attached to a motor capable of rotating subjects slowly through an angle of 90

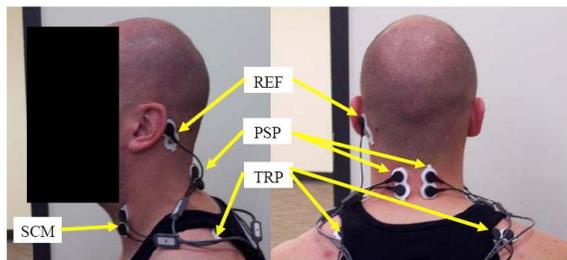


Figure 1. Electromyography (EMG) electrodes were attached to the sternocleidomastoid (SCM), trapezius (TRP), paraspinous (PSP), and a reference (REF).

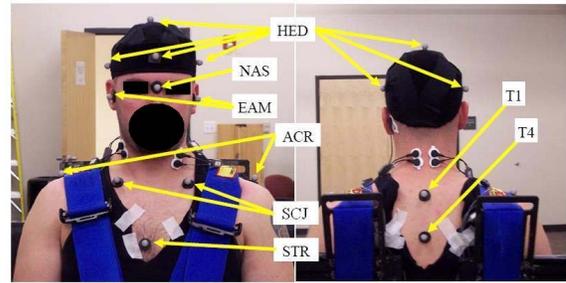


Figure 2. Anterior (left) and Posterior (right) Motion Analysis Marker Placement. Markers were attached to the acromion processes (ACR), four positions on the head (HED), external auditory meatus (EAM), nasion (NAS), sternoclavicular joints (SCJ), mid-sternum (STR), T1, T4, and the seatback top and bottom (not shown).

degrees. The subject was asked to sit in the test apparatus and don the restraints provided. With assistance from a member of the research team, the restraints were adjusted to restrict the motion of the torso, pelvis and lower extremities. An EZ-TILT-2000 rev-2 gravity-based tilt sensor (Advanced Orientation Systems, Inc., Linden, NJ) was placed on the subject's skin between the T1 and T4 markers. This tilt sensor provided real-time measure of the angle of the upper torso with respect to ground, and allowed the researchers to rotate seat of the test apparatus such that the subject's spine reached specific, predetermined angles with respect to ground.

Neck Muscle Relaxation Criteria

The Resting-to-Active Transition Voltage (RATV) was established for each subject as follows to provide an objective assessment of muscle activity. Once secured in the test apparatus with EMG electrodes attached, the subjects were instructed to relax their neck musculature, allowing the neck to flex forward under the influence of gravity. Subjects were coached to relax their neck muscles using the phrase “relax your neck muscles, as if you were asleep” and

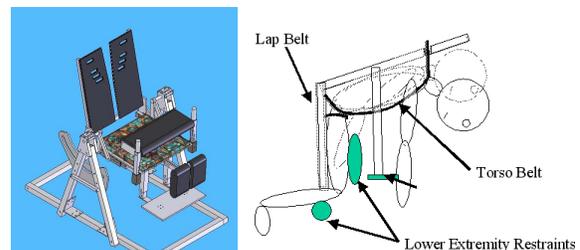


Figure 3. Test Apparatus Design (left) and Function with Occupant (right).

“allow your head to fall forward.” The RATV was initially set as the maximum voltage measured from any of the measured muscle groups in this relaxed state. The subjects were then instructed to voluntarily raise their head up, and the maximum voltage from any of the measured neck muscle groups was noted and the RATV adjusted to this value. This process was repeated iteratively until the all neck muscle voltages were a) just below the RATV value in the relaxed state, and b) just above the RATV as the subjects raised their head from the relaxed state. A smoothing window of 500 ms was used to analyze the data.

Testing Protocol

With the subjects seated and restrained in the test apparatus, before the test began, the subjects were instructed to relax their shoulder muscles during the test, allowing their arms to rest freely in their lap. Subjects were given a countdown after which they were instructed allow their neck to flex while seated upright. Subjects were coached via automated EMG audio feedback to relax their muscles to a state at or below the RATV. Once EMG levels were below the RATV, subjects were instructed to remain relaxed for approximately ten seconds. Throughout the experiment EMG and the target tracking system were continuously recording data. (Note: In the data analysis phase, neck muscle relaxation during the test was reviewed; and if the subject’s muscle activation did not meet certain criteria with respect to the RATV, that subject’s trial was removed from the analysis. This is described further in the Data Reduction section.) Immediately following, the chair portion of the test apparatus was rotated forward until the subject’s spine (vector from T1 to T4) was at 45° relative to ground. Subjects were again coached to relax their neck musculature and allow their necks to flex forward and relax for ten seconds, all while EMG and target tracking data were collected. Subjects were rotated further until their spine (vector from T1 to T4) was parallel to the ground, and coached to relax their musculature, and held in position for ten seconds while EMG and target tracking data were collected. At the conclusion of the three rotations, subjects were returned to the starting position and given a short break, approximately one minute, before beginning the next trial. To acclimate the subject to the test environment, several iterations of the protocol described above were conducted before data were collected. Then, for data collection the previous test sequence was repeated for a total of three trials.

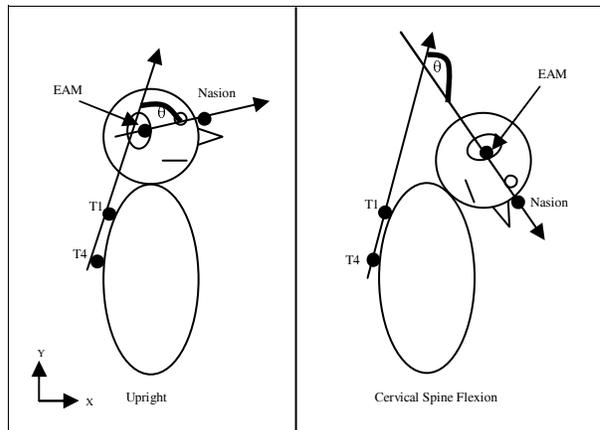


Figure 4. Head vs. Spine Angle Calculation

Data Reduction

The time series motion analysis data for each trial of all subjects were imported into MATLAB (Mathworks, Inc., Natick, MA) for data analysis using a custom written program. A head vector was generated from the midpoint of the left and right EAM markers and the nasion, the seat vector from the upper and lower markers placed on the seatback and the spine vector from the T4 to the T1 marker. The resulting head, seat and spine vectors were projected onto the sagittal plane. The head vs. spine angle was computed as the angle between the head and spine vectors shown in Figure 4. Average angle values were computed during the portions of the trial where the test apparatus was stationary and the subject’s muscle activity remained below his/her RATV for one or more seconds. Conditions and/or trials where the subjects’ paraspinous or SCM muscle activity remained above their RATV, leaving less than one second of relaxation, were eliminated from the head vs. spine angle analysis. Head vs. spine angles were averaged across age groups for comparison.

We postulated that a patient with a disproportionately large head compared to their neck would have greater mass and thus greater forces acting to flex the neck, and thus we calculated the head-to-neck girth (Equation 1) and incorporated this into our analyses.

$$\text{Head-to-Neck Girth} = \frac{\text{Head Girth}}{\text{Neck Girth}} \quad (1).$$

Similarly, we postulated that the slenderness of the neck would also influence its flexibility under load, and thus we calculated the neck slenderness (Equation 2).

$$\text{Neck Slenderness} = \frac{\text{Neck Length}}{\text{Neck Girth}} \quad (2).$$

Statistical Analysis

Anthropometry ratios were imported into SPSS 14.0 (SPSS, Inc., Chicago, Illinois) and SAS 9.2 (SAS Institute Inc., Cary, NC) for statistical analysis. The experiment-wise error rate was held at the 0.05 level. Data were analyzed using both descriptive and inferential statistical techniques. Analysis occurred in three distinct phases. In phase I, descriptive statistics such as frequency distributions, histograms and measures of central tendency, variability, and association were computed for all relevant variables in the dataset. In order to use appropriate statistical methods, variables were tested for normality. In phase II, bivariate plots were generated in which age and head-to-neck girth ratio were plotted against angle for each subject and gender. In phase III, inferential statistical techniques were applied.

A one-way Analysis of Variance (ANOVA) with a Post-Hoc Tukey's Honestly Significant Difference test was used to compare the head-to-neck girth and neck slenderness ratios between the 6-8, 9-12, 20-29, and 30-40 year old groups.

Generalized estimating equations (GEE), with an unstructured correlation matrix, were used to assess the association between age, gender, and head-to-neck girth with passive cervical spine flexion. GEE modeling was used because the design of the study included repeated measures (i.e. multiple trials) for every angle tested (multiple conditions) leading to correlated outcome data. To distinguish between adult and pediatric age groups, analyses were stratified by age (6-12 years old and 20+) for the GEE analyses.

RESULTS

Overall, 38 subjects were enrolled. Sample data including mean age, gender distribution and anthropomorphic ratios for each age group are listed in Table 1.

Age- and Gender-Based Differences in Anthropometry

Results revealed significantly larger head-to-neck girth ratio in 6-8 year olds when compared to 20-30 year old group ($p < 0.01$) and the 30-40 year old group ($p < 0.01$). Similarly, 9-12 year olds exhibited

Table 1.
Age-Based Sample Data

Subjects	Age yrs	Gender M/F	BMI kg/m ²	Head Girth cm	Neck		Head-to- Neck Girth Ratio	Neck Slenderness Ratio
					Height cm	Girth cm		
6-8 Year Old	6	M	15	52	12.7	26.3	1.98	0.48
	6	M	14	52	14.5	27	1.93	0.54
	6	F	16	51	14	26	1.96	0.54
	7	F	16	49.9	14	29	1.72	0.48
	7	F	20	49	14	30	1.63	0.47
	7	M	14	53	14	27.5	1.93	0.51
	8	F	14	49	13	24	2.04	0.54
	8	M	17	54.9	15	30.5	1.80	0.49
	8	F	16	53	17	26	2.04	0.65
Average	7.0	M=4 F=5	16	51.5	14.2	27.4	1.89	0.52
Std Dev	0.9		2	2.0	1.2	2.1	0.05	0.02
9-12 Year Old	9	M	14	53.7	11.5	25.5	2.11	0.45
	9	M	15	51.5	11.6	27.5	1.87	0.42
	10	F	21	55	16.5	28.5	1.93	0.58
	10	M	15	52.5	15	28	1.88	0.54
	10	F	17	53.6	17.3	28	1.91	0.62
	11	F	17	53.5	17	28.3	1.89	0.60
	11	M	20	56	17	32	1.75	0.53
	11	F	20	54.5	16.5	29	1.88	0.57
	12	F	23	55.1	16.5	31.5	1.75	0.52
	12	M	18	55.5	15.5	31	1.79	0.50
Average	10.5	M=5 F=5	18	54.1	15.4	28.9	1.88	0.53
Std Dev	1.1		3	1.4	2.2	2.0	0.03	0.02
20-29 Year Old	20	M	25	58	19.5	39.5	1.47	0.49
	20	M	22	58.2	15.5	36.5	1.59	0.42
	21	M	19	54.5	17.5	35	1.56	0.50
	21	F	25	57	16.5	32	1.78	0.52
	22	M	24	55.5	15.5	36	1.54	0.43
	22	F	20	57.5	20	31.5	1.83	0.63
	22	F	20	55.5	17	31.5	1.76	0.54
	22	M	27	58.5	16.5	41.5	1.41	0.40
	24	F	23	57	12.3	31	1.84	0.40
	26	M	22	58	20.5	36.9	1.57	0.56
Average	22.0	M=6 F=4	23	57.0	17.1	35.1	1.64	0.49
Std Dev	1.8		3	1.4	2.5	3.6	0.05	0.02
30-40 Year Old	31	F	23	56	15	32.5	1.72	0.46
	32	M	28	62	16	41	1.51	0.39
	33	F	23	57.5	18	33.5	1.72	0.54
	34	M	23	56.8	17	37	1.54	0.46
	36	M	26	58.5	21	39	1.50	0.54
	37	F	23	56	13.5	32	1.75	0.42
	37	F	27	59	16	35	1.69	0.46
	40	F	22	56.5	16	34.5	1.64	0.46
	40	F	35	52.5	19	40	1.31	0.48
	Average	35.6	M=3 F=6	26	57.2	16.8	36.1	1.60
Std Dev	3.3		4	2.6	2.2	3.3	0.05	0.02

significantly larger head-to-neck girth ratios compared to the 20-30 year old group ($p < 0.01$) and the 30-40 year old group ($p < 0.01$). No significant differences were found between the 6-8 year old group and the 9-12 year old group ($p = 0.99$). No significant differences were found between the 20-29 and 30-40 year old groups ($p = 0.94$). No significant differences were found in neck slenderness ($p \geq 0.13$).

To detect gender related differences, the 38 subjects were organized into four gender-age groups. Since no significant differences in head-to-neck girth were found between the 6-8 and 9-12 year age groups or between the 20-29 and 30-40, the 6-12 year olds and the 20-40 year olds were combined into single

Table 2.
Gender-Based Sample Data

Subjects	Age yrs	Gender M/F	BMI kg/m ²	Head Girth cm	Neck		Head-to- Neck Girth Ratio	Neck Slenderness Ratio	
					Height cm	Girth cm			
Female Pediatric	6	F	16	51	14	26	1.96	0.54	
	7	F	16	49.9	14	29	1.72	0.48	
	7	F	20	49	14	30	1.63	0.47	
	8	F	14	49	13	24	2.04	0.54	
	8	F	16	53	17	26	2.04	0.65	
	10	F	21	55	16.5	28.5	1.93	0.58	
	10	F	17	53.6	17.3	28	1.91	0.62	
	11	F	17	53.5	17	28.3	1.89	0.60	
	11	F	20	54.5	16.5	29	1.88	0.57	
	12	F	23	55.1	16.5	31.5	1.75	0.52	
	Average	9.0	F=10	18.1	52.4	15.6	28.0	1.9	0.6
	Std Dev	2.1		3.0	2.4	1.6	2.2	0.1	0.1
Female Adult	21	F	25	57	16.5	32	1.78	0.52	
	22	F	20	57.5	20	31.5	1.83	0.63	
	22	F	20	55.5	17	31.5	1.76	0.54	
	24	F	23	57	12.3	31	1.84	0.40	
	31	F	23	56	15	32.5	1.72	0.46	
	33	F	23	57.5	18	33.5	1.72	0.54	
	37	F	23	56	13.5	32	1.75	0.42	
	37	F	27	59	16	35	1.69	0.46	
	40	F	22	56.5	16	34.5	1.64	0.46	
	40	F	35	52.5	19	40	1.31	0.48	
	Average	30.7	F=10	24.2	56.5	16.3	33.4	1.7	0.5
	Std Dev	7.8		4.5	1.7	2.4	2.7	0.2	0.1
Male Pediatric	6	M	15	52	12.7	26.3	1.98	0.48	
	6	M	14	52	14.5	27	1.93	0.54	
	7	M	14	53	14	27.5	1.93	0.51	
	8	M	17	54.9	15	30.5	1.80	0.49	
	9	M	14	53.7	11.5	25.5	2.11	0.45	
	9	M	15	51.5	11.6	27.5	1.87	0.42	
	10	M	15	52.5	15	28	1.88	0.54	
	11	M	20	56	17	32	1.75	0.53	
	12	M	18	55.5	15.5	31	1.79	0.50	
	Average	8.7	M=9	15.9	53.5	14.1	28.4	1.9	0.5
	Std Dev	2.1		2.1	1.7	1.8	2.3	0.1	0.0
	Male Adult	20	M	25	58	19.5	39.5	1.47	0.49
20		M	22	58.2	15.5	36.5	1.59	0.42	
21		M	19	54.5	17.5	35	1.56	0.50	
22		M	24	55.5	15.5	36	1.54	0.43	
22		M	27	58.5	16.5	41.5	1.41	0.40	
26		M	22	58	20.5	36.9	1.57	0.56	
32		M	28	62	16	41	1.51	0.39	
34		M	23	56.8	17	37	1.54	0.46	
36		M	26	58.5	21	39	1.50	0.54	
Average		25.9	M=9	24.0	57.8	17.7	38.0	1.5	0.5
Std Dev		6.4		2.8	2.1	2.1	2.3	0.1	0.1

pediatric and adult age groups, respectively, and then separated by gender. Gender-based sample data including mean age, gender distribution and anthropomorphic ratios for each age group are listed in Table 2.

Results revealed significantly larger head-to-neck girth ratio in pediatric males when compared to adult males ($p<0.01$). Similarly, pediatric females exhibited a significantly larger head-to-neck girth ratio ($p=0.02$) compared to adult females. Statistically significant differences were found in head-to-neck girth ($p=0.01$) between adult males and adult females. Significant differences were found between pediatric females and adult males ($p<0.01$)

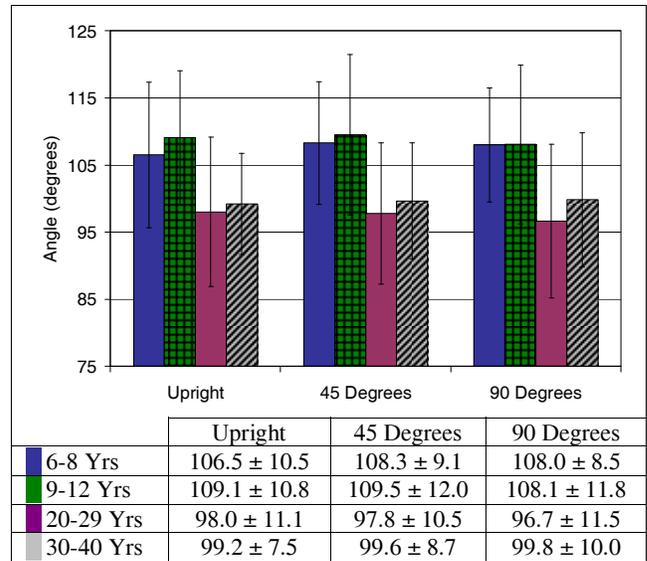


Figure 5. Age-based angle comparison.

and between pediatric males and adult females ($p<0.01$). No significant differences were found between pediatric females and pediatric males ($p=0.99$).

No significant differences were found in neck slenderness between pediatric females and males ($p=0.12$), adult females and males ($p=0.78$), pediatric and adult females ($p=0.07$), pediatric and adult males ($p=0.70$) or pediatric male and adult female ($p>0.99$). A statistically larger neck slenderness ratio was found in pediatric females compared to adult males ($p<0.01$).

Age- and Gender-Based Differences in Cervical Flexion

The head vs. spine flexion angle means and standard deviations for each age group are illustrated in Figure 5. Combining 38 subjects with three trials and three conditions yielded the potential for 342 total data points (81 in the 6-8 yr olds, 90 in the 9-12 yr olds, 90 in the 20-29 yr olds and 81 in the 30-40 yr old group). Conditions and/or trials that violated the relaxation criteria were eliminated, reducing the number of data points to 295 (55 in the 6-8 yr olds and to 69 in the 9-12 yr olds). No data were eliminated from the adult groups.

The head vs. spine flexion angle means and standard deviations for the gender-age groups are illustrated in Figure 6. Eliminating data points that violated the relaxation criteria yielded 76 in the female pediatric group, 90 in the female adult group, 48 in the male pediatric group, and 81 in the male adult group for a total of 295 data points.

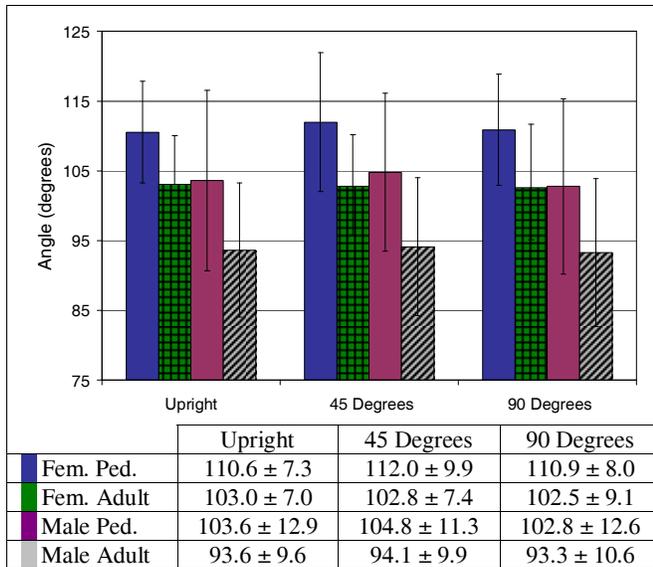


Figure 6. Gender-base angle comparison.

Differences in cervical flexion angle were demonstrated for both gender and age; females exhibited larger neck flexion angle than males ($p = 0.013$) and flexion angle decreased with age ($p = 0.006$). There was no significant interaction between age and gender ($p = 0.76$). Head-to-neck girth ratio in part explained these differences. Adding this to the model yielded a significant effect ($p = 0.004$), and eliminated both the effect of age ($p = 0.39$) and gender ($p = 0.13$). Of note, condition (upright, 45°, 90°) and trial number had no effect on flexion angle ($p = 0.45$ and $p = 0.72$, respectively).

To illustrate the change in head vs. spine angle across age, all trials and conditions meeting the relaxation criteria were plotted across age for males and females in Figure 7.

Stratifying the analyses by age groups revealed that the gender effect remained significant only in the adult group ($p = 0.04$); no gender effect was seen ($p = 0.18$) among the 6-12 year olds. Within the pediatric age group, an increased head-to-neck ratio resulted in significantly more cervical flexion ($p = 0.024$).

DISCUSSION/CONCLUSION

This study utilized pediatric and adult human volunteers and demonstrated significant decreases in passive cervical spine flexion with age for both males and females. Gender differences were present among adults - adult females exhibited significantly greater flexion than males. This trend was present in pediatric data, but was not statistically significant. The age and gender differences were explained in

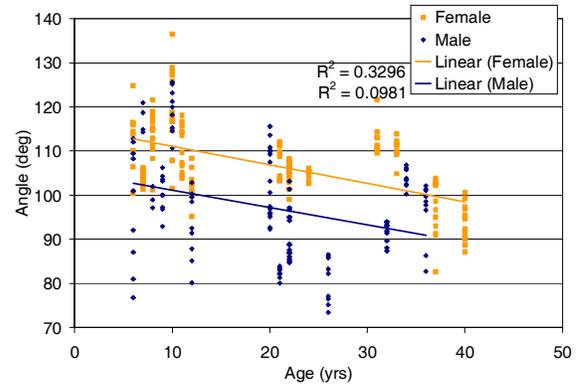


Figure 7. Head vs. Spine Angle vs. Age

part by differences in the head-to-neck girth ratio. This parameter which decreased with age and was greater in females versus males was the most significant contributor to the decrease in cervical spine flexion.

Previous PMHS and PMAS studies have shown that tensile strength increased with age (Ching et al., 2001; Hilker et al., 2002; Nuckley et al., 2005; Ouyang et al., 2005; Nuckley and Ching, 2006). While our study was an external measurement of cervical spine flexion, these internal findings may help explain our results. Increased tensile stiffness in the adult population could result in reduced strain of the cervical spine ligaments and passive musculature, decreasing overall flexion angle. Contrarily, reduced tensile stiffness in the pediatric age range would lead to greater strain and greater neck flexion. Greater neck flexion in children is also likely due to their increased head-to-neck ratio as compared to adults which would yield greater neck loads and increased tension on the passive neck musculature. Further biomechanical analysis is required to detect correlations between neck loads, neck flexion, and head-to-neck dimensions.

Unlike Arbogast et al (2007) we found no significant differences between the 6-8 year old group and 9-12 year old group. This difference may be attributed to the addition of active musculature, as motor control improves with maturation.

Previous studies have reported no gender based differences in pediatric cervical spine range of motion (Feipel et al., 1999; Lewandowski and Szulc, 2003; Arbogast et al., 2007). This study showed a trend towards increased flexion in pediatric females compared to pediatric males, however these differences were not statistically significant. The lack of statistical significance may be due to an insufficient sample size as a total of 47 data points

were removed from the possible 171 in the pediatric age range due to exceeding the relaxation criteria. Of interest, if the relaxation criteria is waived and all trials of all pediatric subjects are included, gender has a significant effect on cervical spine flexion among children ($p=0.02$). This may suggest differences in muscular control between the genders that may have an influence on neck kinematics. Future studies are needed to fully understand gender based differences in neck flexion among pediatric subjects.

The paucity of pediatric post-mortem human subjects for biomechanical research necessitates other methods for obtaining pediatric data. Sub-injurious human volunteer studies like those described herein compliment the rare PMHS data and animal studies. These data quantify the changes in passive cervical spine flexion across maturation and act as a validation data set for computational cervical spine models. Ultimately, these data will contribute to the development of an improved pediatric ATD biofidelity requirement.

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