Pediatric Neck Muscle Strength and Endurance

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ABSTRACT

Pediatric head injuries, the leading cause of death in children, have been difficult to model and develop preventative interventions because of a lack of biomechanical data. Neck mechanics is central to head injury prevention since it is the musculoskeletal neck, which dictates the position and movement of the head. Classically, geometrical scaling has been used to develop child injury prevention strategies. Child head injury prevention is particularly difficult due to the differential head-to-body allometry – head circumference of a 4-year-old is 90% of its adult value while the neck circumference, for example does not approach 90% of adult until age 14. Therefore, the objective of this human-subject study was to measure the anthropometry and mechanics (strength and endurance) of the developing neck musculature. A factorial study design was performed on 69 human subjects where anthropometry (height, weight, and head-neck dimensions) was recorded and strength and endurance were measured in three directions (flexion, extension, lateral bending) as a function of age (6-24 years). Using a custom designed testing device, including a six-axis load cell, each subjects' neck maximum voluntary contraction was measured in triplicate. Following this test, an endurance test measured the subjects' ability to apply 70% of their peak force for 30 seconds. Linear regression of peak force ($p<0.012$) and endurance ($p<0.003$) as a function of age revealed each direction to be statistically increasing with age (F-test). The peak force, averaged across direction, advanced with age by the following function: Average Peak Force (N) = 2.34(age) +35.29. Similarly, the endurance (percentage of peak force at 30 seconds) exhibited the following function with age: %Peak Force = 1.58(age) +29.66. The anthropomorphic measurements also increased with age similar to data found in the literature. Our results predict that a 4-year-old child with a 90% adult head size is only capable of producing 54% of the adult peak neck force. Further, the child neck muscles appear to fatigue earlier than adults. These relationships will facilitate more accurate modeling of the head-neck complex and improved design of head injury prevention interventions.

INTRODUCTION

The leading cause of death for children under the age of 24-years (15,000 each year) is traumatic injury (Motor Vehicle Traffic Crashes 2003, Langlois and Sattin 2005, P.H.S 2000). Of these, most succumb to head injuries. Children who survive head and neck trauma are left with physical, emotional and financial burdens. These injuries are the result of motor vehicle crashes, sport accidents, and falls, all of which may be prevented. Helmets and safety standards have been developed to mechanically protect a child's head and neck; bicycle helmets have been shown to reduce the risk of non-fatal head injuries by 75% (Safe 2005).

These safety interventions have been developed largely in the absence of pediatric biomechanical data for head and neck. Instead, adult data have been scaled down to represent the child in the development of these injury prevention strategies. This geometric scaling of adults to represent the child may not be adequate when head injury prevention is concerned; the head-to-body relationship of a developing child is significantly different than that of an adult. This discrepancy is unmistakable in child head-to-neck allometry – head circumference of a 4-year-old is 90% of its adult value in contrast the neck is only 75% of its adult size by age 4 and 85% at age 12 (Arbogast, et al. 2005). An accurate understanding of head and neck allometric biomechanical growth trajectories would allow us to implement better predictive models that could engender advanced injury prevention strategies.

The growth transformation of the anatomic geometry of the pediatric cervical spine has been well documented. There have been a couple studies looking at the radiographs of the developing pediatric cervical spine. These studies document the radiographic changes in the cervical vertebrae in children as they mature. With the developing neck the vertebral bodies increase in height from the age of six months to maturity, but the growth is most significant in the first five years. It was also found that the cervical canal grows rapidly during the first three years of life, by which time it has reached nearly 95% of its mature diameter (Wang, et al. 2001, Pintar, et al. 2000, Ching, et al., 2001, Rankin, et al., 2005).

Neck mechanics is central to head injury prevention since it is the musculoskeletal neck that dictates the position and movement of the head. A number of studies have examined the osteoligamentous cervical spine as it matures from infancy to adulthood using animal models (Ching, 2001, Nuckley 2002, Nuckley 2004, Pintar, 2000). Pediatric neck musculature has not received the same attention in the literature in spite of their role in the control and support of the head, which is a relatively large mass in children. The biomechanics of this system depends on the neck muscle's ability to withstand large forces over prolonged periods of time. With the neck controlling the head's positioning in space it is important to know whether the child neck is capable of supporting more mass such as a helmet. Thus, identifying neck muscle strength and endurance will facilitate enhanced understanding of pediatric head-neck injury biomechanics.

Many studies have examined the muscles of the cervical spine; the majority of these have focused on adults and the degenerative effects of aging (Boyd-Clark, et al. 2002, Rankin, et al. 2005). These studies identified the isometric neck muscle strength in adults. Each study used a different testing mechanism, but the main objectives were to identify the maximum forces and moments generated by the neck in various directions (Vasavada et al. 2001, Suryanarayana and

Kumar 2005, Kumar et al. 2001, Valkeinen 2002). The general findings are that strength differs in each direction with extension having the highest forces. Only a few studies focused on endurance (Faigenbaum, et al. 2005, Lee 2005), where the subject was asked to apply a particular force and maintain it for as long as they could. The length of time was then compared to other variables.

While no studies specifically examining pediatric cervical muscle mechanics were identified, there are several pediatric studies involving muscle strength of the upper and lower body as well as trunk flexion. Carron et al. (1974) tested the upper and lower strength on boys between the ages of 10 to 16 years. It was found that the general strength did not change between the ages when height and weight were factored out but that there was a difference in strength compared to maturity level. Lefkof et al. (1986) studied 160 children between the ages of 3 to 7 years old and measured the strength of their trunk flexor muscles. Their findings showed that strength was different between the age groups and that it increased with age. There is a general consensus that muscle strength increases with maturation, if this trend can be seen in other muscle groups in children, it can possibly be seen in their neck muscles as well. Using the techniques and concepts from adult tests, the pediatric neck muscle strength and endurance can be characterized and correlated with anthropometrical and age metrics.

Therefore the goal of this study was to identify the developmental biomechanics of the musculoskeletal neck and relate these with child head and neck anthropometry. This human subject study focused on measuring the anthropometry of the developing head and neck as well as the neck muscle strength and endurance.

METHODS

A factorial study design was used to examine neck anthropometry and muscle strength and endurance in a maturing population (6-to-23-years). This methodology received approval by the University of Washington Human Subjects Review Committee (approval no. 05-5292-E/C 01) and the following methods meet all requirements stipulated by HRB. The first phase was to measure the anthropometry of the subjects' head and neck. The second phase focused on measuring the subject's maximal voluntary contraction (MVC) of their neck muscles using a custom designed testing apparatus. Finally, the third phase evaluated the subject's neck muscle endurance by evaluating their ability to hold 70% of the peak MVC over 30 seconds.

Subjects and Recruitment

The test sample included 69 subjects ranging from 6 to 23 years old. The sample size was of mixed gender. These subjects were divided into three age groups 6-11, 12-17, and 18-23 and recruited from local Seattle Public Schools (Green Lake Elementary, TOPS at Seward, and Nathan Hale High School) and the University of Washington. Recruitment processes included distributing flyers and letters to local schools and communities. This allowed potential subjects the opportunity to contact the researchers and ask questions, eliminating any source of coercion. All willing participants were informed about the testing process including the use of digital video recordings and submitted consent/assent forms.

Instrumentation
The goal of the testing device was to isolate and measure forces exerted by the subject's neck muscles. The head device, attached to a chair, was placed around the subject's head to measure their neck strength at upright neutral posture. The headpiece is a set of three bars with padded buttons that are positioned at three points around the subject's head: forehead, above their left ear and back of their head. A picture of the head device and chair can be seen in figures 1 and 2. The head device is attached to a 6-axis load cell measuring forces and moments in flexion, extension, and lateral bending. This device is adjustable for subjects of various sizes. The testing chair is not outfitted with a restraint system, preliminary tests showed that a restraint system did not influence the data and as a result was removed for the comfort of the subjects.

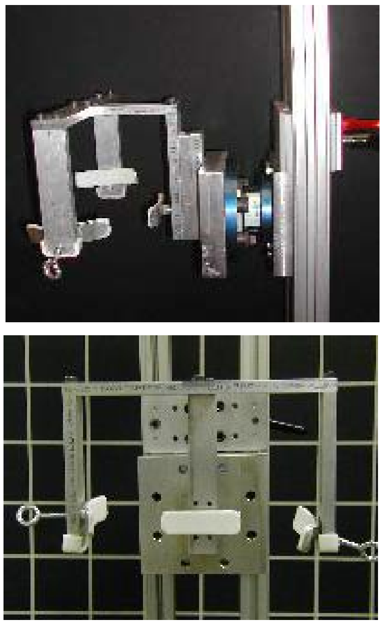

Figure 1. Head Device

Figure 2. Head Device and Chair

To validate the load cell's measurements a uni-axial load cell was placed on each of head buttons, representing flexion, extension, and lateral bending. A force was applied to this load cell. The input force recorded by the uni-axial load cell was known and then compared to the 6-axis load cell measurements. A summation of forces and moments were calculated to verify the measurements. The force and moment data were acquired using a custom LabVIEW virtual instrument on an NI-DAQ USB device with 16-bit resolution. The virtual instrument enabled the collection of each subject's identification number, anthropometry, and force/moment data for each test. In addition to the testing instrumentation, anthropometric measurements are taken using a height-weight scale, tape measures, and head-neck calipers. During the procedure each subject will be videotaped with his or her consent.

Phase I: Anthropometric Measurements
Basic anthropometric measurements were taken for each subject. The subjects were asked to remove their shoes and step onto a height-weight scale where their height (cm) and weight (lbs) were measured. All head measurements were done according to the work by Brandtmiller et al. (1995) including head circumference, breadth, and height. As there is no current standard for

neck measurements, neck circumference and length (C7 spinous process – to – external auditory meatus) were recorded for comparison purposes.

Phase II: Voluntary Maximal Contraction

Each subject was read an oral consent to which they responded whether or not they want to participate. The researchers explained and demonstrated the proper way to flex and extend their necks. After the demonstration they were given an opportunity to warm up their neck muscles with some basic stretching. They were seated in the testing chair and the head device was lowered around their head about a ¼" above their brow. The pads were adjusted so that they were in contact with the head yet still allowing the subject to comfortably move their head. Subjects were asked to extend their legs and rest their heels on a footrest with their toes pointing up. They were also instructed to sit up tall with a straight back and have their hands placed folded in their lap. This position helped to isolate their neck muscles. We did not want them to push with their legs or hands. Each subject was asked to push his or her head forwards (flexion), backwards (extension) and to the side (lateral bending) to help them to adjust to the testing chair. Once the subject felt comfortable they were asked to push their head in each direction to their voluntary maximum contraction. They were asked to do each direction three times in a randomized order with a break between each test. Subjects were instructed to push as hard as they could without straining their neck muscles and without feeling uncomfortable. The data was collected at 40 Hz over 10 seconds and saved. This phase of tests took approximately 10 minutes. During the rest periods the subjects were reminded of their posture and asked about their sports participation and activity level.

Phase III: Neck Muscle Endurance

This phase measured the endurance of the subject's neck muscles. Endurance was defined herein as the measurement of the percent of maximal force the muscles were able to apply at the end of a 30 second trial. The subjects were asked to push 70% of their previous maximal force and maintain that force for 30 seconds. This test was monitored by a voltmeter, which allowed for real time feedback of the subjects' forces. When the subject reached the targeted force they were instructed to hold what they were pushing. Data was collected for 30 seconds. This test was repeated once for each direction. Subjects were given the opportunity to rest their neck muscles between each test. With the final phase completed subjects asked to stretch their neck muscles with basic stretching moves. They were also given the opportunity to ask final questions. The subjects were given a copy of their consent forms, their identification number, and a $10 compensation.

Data Analysis

The raw force and moment data are initially transformed to the forces applied at each button. The maximal voluntary contraction (peak force) experiments involved averaging three consecutive points at the peak of the subject's maximum force trial for each direction. The peak force is defined as the maximum point with at least a 0.1sec rise. The endurance force data are divided by the peak force to accurately approximate the percentage of MVC over time. This methodology is similar to the work of Yamaji et al. (2005). The neck muscle force percent of maximum was then calculated from the mean of the final 10 data points on the filtered endurance trial.

RESULTS

The anthropomorphic measurements taken for each subject correlated with the growth trajectories found in the literature (Brandtmiller, 1995, CDC 2000). Figures 3 and 4, demonstrate that our subjects, when compared to the Brandtmiller and CDC growth charts, represent a normal population.

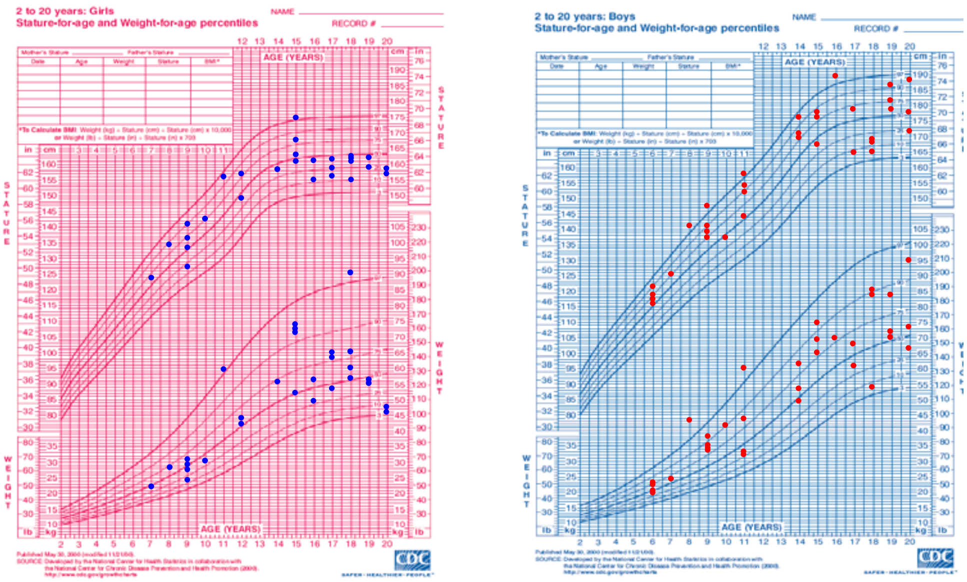

Figure 3. Height and weight CDC growth charts A. Females B. Males.

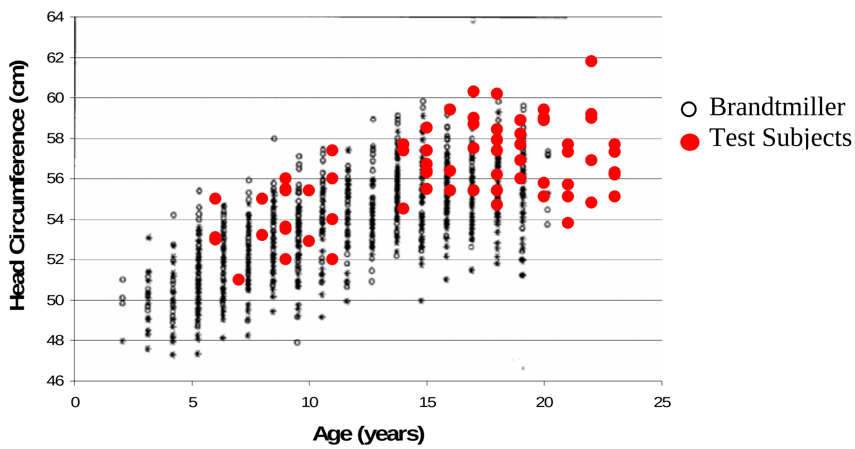

Figure 4. Head Circumference of test subjects compared to Brandtmiller's study.

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Figure 5 shows the normalized head circumference and neck circumference in relation to age.

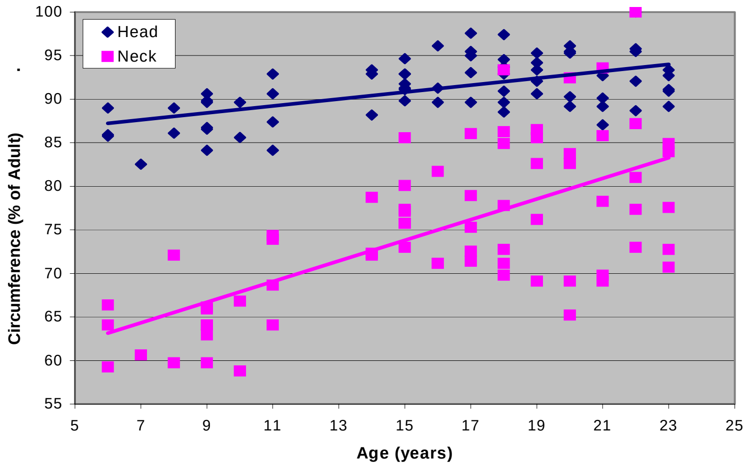

Figure 5. Head and Neck Circumference vs. Age

The voluntary maximal contraction for each subject was measured for each direction in triplicate. Representative data plots are shown in figure 6 and 7 demonstrating the differences between a 7year old male and 22year old male.

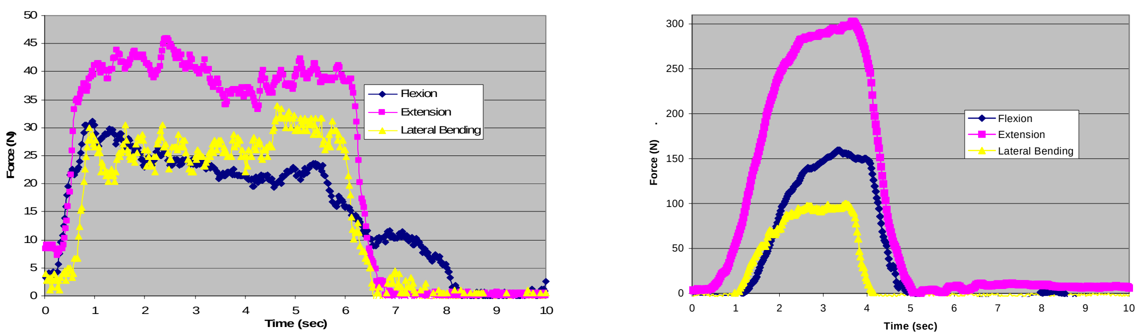

Figure 6. Maximum Voluntary Contraction Force Time Histories for Flexion, Extension, Lateral Bending (7 year old, 22 year old)

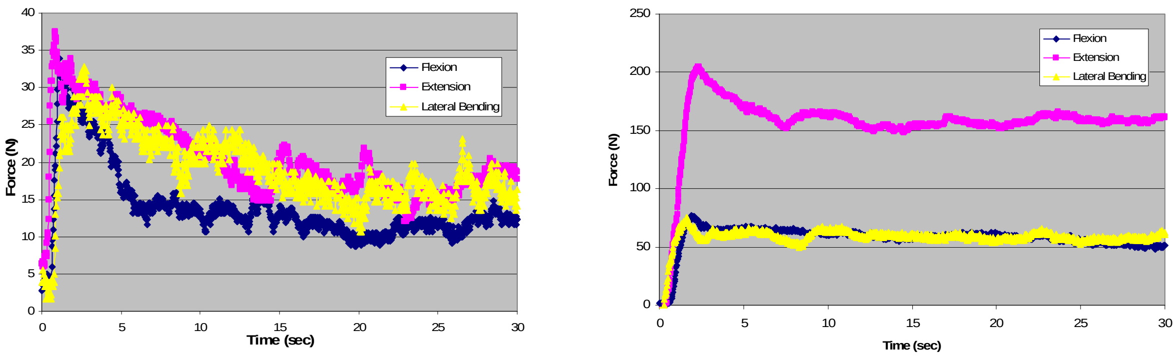

Figure 7. Endurance Time History: 70% of Peak Force being held for 30 sec. (7 year old, 22-year old)

A linear regression of peak force ($p<0.012$) as a function of age revealed each direction (flexion, extension, and lateral bending) to be statistically increasing with age (F-test). Figure 8 shows the peak force for each direction graphed against age. A linear regression line for the average of the forces was plotted and function is

Average Peak Force (N) = 2.34(age) +35.29.

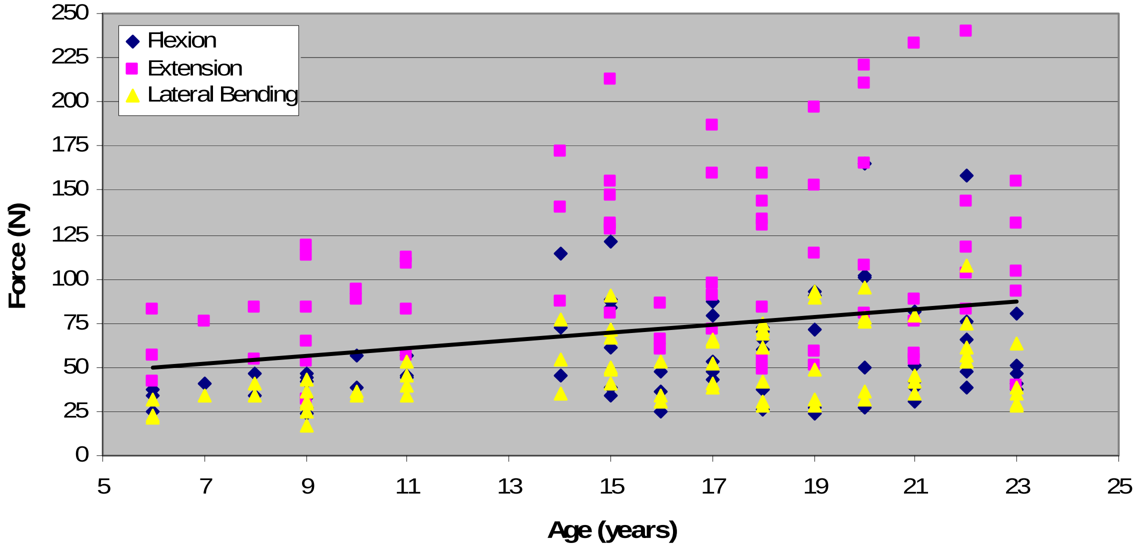

Figure 8. Peak Forces for Flexion, Extension, Lateral Bending vs. Age.

A linear regression for endurance ($p<0.003$) as a function of age revealed each direction to be statistically increasing with age (F-test). The endurance, which is defined as the percentage of peak force at 30 seconds, exhibited the following function with age:

%Peak Force = 1.58(age) +29.66, this can be seen in figure 9.

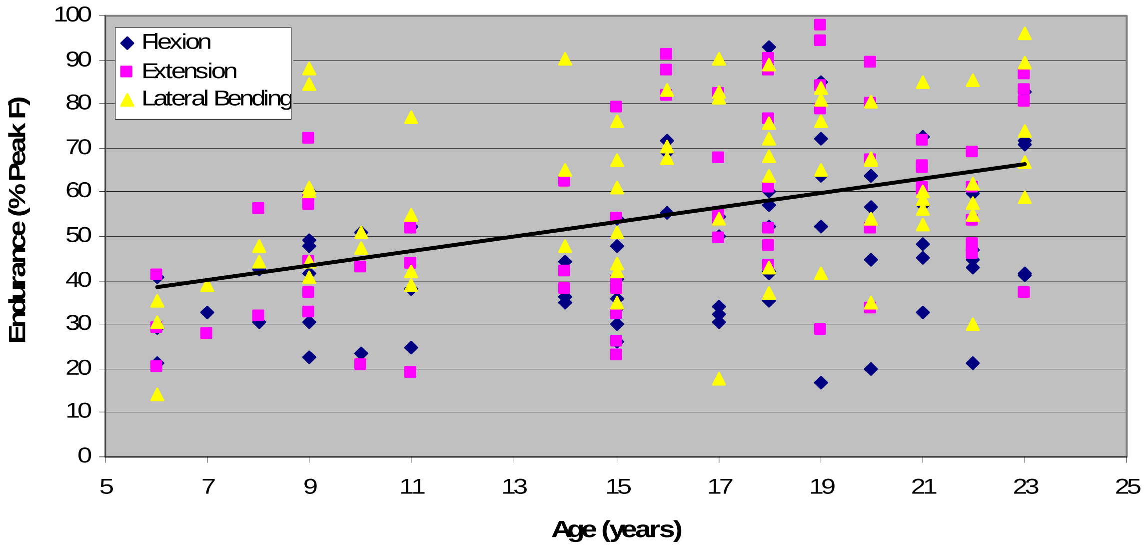

Figure 9. Endurance: % of Peak Force after the 30 sec. vs. Age.

In addition to the graphical representation of the data, the following table shows the subjects' average force (N) data by direction, age, and gender.

Table 1. Peak and Average Forces (N) for each age group.

		6-11 Years Old			12-17 Years Old			18-23 Years Old		
		Flexion	Extension	Lateral	Flexion	Extension	Lateral	Flexion	Extension	Lateral
Female	Mean	36.7	71.7	30.8	48.3	93.1	44.2	38.6	79.4	39.1
	Max	56.2	111.4	44.7	87.8	131.7	71.0	66.0	143.8	61.6
	Min	20.6	53.1	21.9	26.6	43.9	24.3	24.1	40.0	28.5
	Stdev	14.1	22.0	8.0	16.1	27.2	11.9	11.5	29.4	11.9
Male	Mean	38.3	77.4	32.9	79.2	147.0	61.0	83.9	164.0	69.7
	Max	56.3	118.3	53.0	121.5	213.2	91.0	165.7	301.3	107.0
	Min	23.8	32.0	16.6	25.0	60.3	28.8	42.0	57.6	35.0
	Stdev	8.6	26.3	9.2	30.8	47.4	20.4	34.2	67.0	20.8

DISCUSSION

This study achieved its goal by measuring the developmental biomechanics and anthropometry of the pediatric musculoskeletal neck. Research has identified growth trajectories for the head-to-body allometry; however, until now, the effects of maturation on neck mechanics and the neck's ability to hold and move the head have not been previously appreciated. The child's maximum voluntary contraction has been shown to increase with age. Likewise neck endurance appears to increase with advancing maturity. Comparison of our adult data with the literature reveals similar trends and values, validating our experimental procedures. Post-hoc analyses of direction of loading and sex reveal trends also present in the adult populace; the extension direction produces higher forces than the other directions and females produces less force than the males. This study has shown what forces the child neck is capable of producing and sustaining as they develop into adulthood.

The adult force data, table 1, is similar to the force data collected by Valkeinen (2002) for flexion (151 ± 47N) and extension (278 ±50N); lateral bending was not tested. The adult data of this study was also compared to Kumar et al. (2001) and Vasavada et al. (2001). Kumar's data for flexion (72 ± 18N) and left lateral bending (76 ± 23 N) were comparable to this study's data; however the male extension forces for the adult group were less than what was observed herein. Vasavada's study recorded the force moments about the C7-T1 vertebral level for adults (30 years old). A comparison of the moments showed that Vasavada's data were slightly larger than this study's. It has been recognized that the methodologies and testing devices in these studies are different than those used in this study and could contribute to the differences seen in the force data. Comparisons of these studies have shown that the adult data collected are comparable to other studies and therefore validates our methodology and supports the child (6-17 years old) data.

This study was a baseline study, to our knowledge the first to incorporate pediatric neck muscle strength, therefore the limitations of this study have been recognized and suggestions made for future studies. The major limitation of this project was the subject's effort and attention. The children were explained the procedures and understood the process, however, without any verbal or visual stimulation it is thought that the subjects lost interest during the endurance test and the data may not actually reflect fatigue but inattentiveness. To improve the outcomes of this study it is suggested that the next study incorporate EMG to confirm muscle fatigue by having data that reflects the level of muscle activity. The recruitment process of this study may have incorporated a bias to this study. Subjects that volunteered to participate were generally active, participating in one or more sports, and in good health. This is not representative of the general population. Finally, this study tested subjects in an upright neutral position. This provides us with a basic understanding of what the neck is capable of but does not provide information regarding the range of motion and applicable forces. The next phase of this study should also include a testing device that allows the subject to apply forces at varying angles. This study provided an understanding of how the child neck develops and the basic mechanics of the head and neck system. This study provides the foundation for other pediatric human subject studies.

As discussed a child of 4 years old can only produce approximately 54% of that of an adult. This is significant when designing protective gear and implementing safety standards for children. It is important to keep in mind that the child is not simply a scaled down version of an adult, but physiologically different. The strength and endurance tests applied herein provide an excellent first look at neck muscle mechanics as it changes with growth and development. This information can be used to enhance computational models, which will allow us to better predict child head and neck injuries in hopes of developing and implementing advanced interventions of child injury prevention.

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