The Compressive Stiffness of Human Pediatric Heads

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Abstract

Head injury is a persistent and costly problem for both children and adults. Globally, approximately 10 million people are hospitalized each year for head injuries. Knowing the structural properties of the head is important for modeling the response of the head in impact, and for providing insights into mechanisms of head injury. Hence, the goal of this study was to measure the sub-injurious structural stiffness of whole pediatric heads. Twelve cadaveric pediatric (20-week-gestation to 16 years old) heads were tested in a battery of viscoelastic compression tests. The heads were compressed in both the lateral and anterior-posterior directions to 5% of gauge length at normalized deformation rates of 0.0005/s, 0.01/s, 0.1/s, and 0.3/s. Because of the non-linear nature of the response, linear regression models were used to calculate toe region (<2.5%) and elastic region (> 2.5%) stiffness separately so that meaningful comparisons could be made across rate, age, and direction. The results showed that age was the dominant factor in predicting the structural stiffness of the human head. A large and statistically significant increase in the stiffness of both the toe region and the elastic region was observed with increasing age ($p < 0.0001$), but no significant difference was seen across direction or normalized deformation rate. The stiffness of the elastic region increased from as low as 5 N/mm in the neonate to >4,500 N/mm in the 16 year old. The changes in stiffness with age may be attributed to the disappearance of soft sutures and the thickening of skull bones with age.

Keywords: head, compression, biomechanics, pediatric, stiffness

Introduction

Head injury is a persistent and costly problem. Globally, approximately 10 million people are hospitalized each year for head injuries—in the United States alone, 1.1 million people are hospitalized annually (Langlois et al., 2006b; Murray and Lopez, 1996). Children and young adults under the age of 20 suffer the majority of these injuries (Langlois et al., 2006a). It is estimated that 3% of all children will experience a brain injury by the time they turn sixteen years old (Kraus, 1995). Despite this, there is very limited quantitative data on the structural properties of the pediatric head (Prange et al., 2004). Knowing the head's structural properties is essential to understanding its response to loads and, consequently, the mechanical exposures for which skull anatomical changes with age are based (Lapeer and Prager, 2001; Prange et al., 2004).

In previous work on adult heads, McElhaney conducted quasi-static ($\sim 0.0005/s$) compression failure tests on 23 specimens. He found that the average peak force at fracture was 5115 N and 5954 N in the lateral and anterior-posterior directions, respectively, with compression strains of $\sim 2\%$ of head length and $\sim 4\%$ of head width (McElhaney, 1976; McElhaney et al., 1972). Additionally, head stiffness was observed to be nonlinear (McElhaney, 1976; McElhaney et al., 1972). Yoganandan et al. (1995) studied adult head compression using a hemispherical anvil while the lower portion of the head was rigidly fixed (Yoganandan et al., 1995). The heads were loaded locally with direct contact to the vertex, temporal, occiput, and frontal bones at rates of 0.0025 m/s and at 7.1–8.0 m/s. This experiment showed that head stiffness and fracture force increased with deformation rate, while the deflection to failure decreased with deformation rate (Yoganandan et al., 1995). To date, no study has evaluated how head stiffness changes with age or evaluated the stiffness of heads between the ages of 1 month and 18 years old.

117 The goal of this study was to quantify the structural stiffness of human pediatric heads
118 from birth through age 16. The variables examined include age, compression direction,
119 compression amount, and normalized deformation rate. These data are valuable for understanding
120 the compressive response of the pediatric head, and are useful in developing computational
121 models, anthropomorphic test devices (ATDs), and scaling relationships.

122

Methods

Twelve pediatric cadaveric heads were used in this study (Table 1). Data from a previously published study was also included (Prange et al., 2004)(P03M, P05F, and P06F). The specimens were obtained from nonprofit donor institutions including Duke University. The IRB was apprised of the research and protocol, but approval was not needed because cadavers are not considered human subjects. These specimens were fresh-frozen and stored at -20°C. Before testing, they were thawed in a humidified chamber. The head tests were performed following a series of neck tension tests that required removal of the mandible (Dibb et al., 2009; Luck et al., 2008). First, the head was disarticulated from the neck at the occipital condyles and dimensions of the head (head width, head length, and circumference) were measured. The head width and length were measured using calipers while the circumference was measured using measuring tape. The skull thickness was measured using CT scans (AMIRA, FEI Software, Hillsboro, OR) at the forehead (slightly below the hairline), vertex (at the apex along the sagittal suture), and at the occiput and parietal bones near the impact sites. Saline-soaked gauze was used to loosely plug the foramen magnum. The head was placed between two ¾ inch thick polished aluminum platens in a hydraulic actuator (MTS Systems, Eden Prairie, MN). For the anterior-posterior (AP) compression tests, each head was placed with the occiput touching the bottom platen and the forehead touching the top platen; for the lateral compression tests, each head was placed with the parietal regions in contact with the platens (Figure 1). If the heads were too unstable in the AP direction, the compression tests were not run (P18M, P21F). Loads were measured using a 900 N uniaxial load cell (BLH Electronics U3G1 SN: 62974) and displacements were measured using the MTS' internal linear variable differential transformer (resolution ±0.1 mm) (Schaeffler Sensors, Hampton, VA).

The compression test battery consisted of a preconditioning test (McElhaney et al., 1983) and four constant velocity displacement controlled tests (0.0005/s, 0.01/s, 0.1/s, 0.3/s) to a peak deformation of 5% of the compressed dimension. The loading rates were normalized using head gauge lengths: the maximum head width or head length, respectively (Table 1). Normalized displacement rates were used to produce constant structural strain rates across various sizes of heads and were based on the rates used by Prange (Prange et al., 2004). Depending on specimen size, the ram velocity ranged from 0.05 to 0.10 mm/s, 0.7 to 1.9 mm/s, 7 to 19 mm/s, and 22 to 57 mm/s for the 0.0005/s, 0.01/s, 0.1/s, and 0.3/s normalized deformation rates. The rates were the same for both loading and unloading. A preload of between 0.5 N and 1 N was applied prior to each test to ensure contact with the platens. The first step in the test battery was to precondition the heads with cyclic loads from 0% to 2.5% compression at 1 Hz for 60 seconds. The testing battery for each direction always commenced with the preconditioning tests, after which the normalized deflection rate tests were run consecutively in order of increasing velocity. Between each test, a recovery time of at least the length of the prior test took place. The sample rates were 150 Hz for the 0.0005/s preconditioning tests and 10,000 Hz for the remaining tests. Load and displacement interlocks were set to ensure the heads were not fractured so that subsequent drop testing could be conducted (Loyd, 2011). The displacement interlocks were 5% of the gauge length, and the force interlocks were 500 N. After each test, the head was palpated and the data were checked for discontinuities that would indicate fracture.

For analysis, all data were digitally filtered using a low-pass Butterworth filter with a cutoff frequency of 100 Hz. Non-linear regressions were computed for the complete loading portion of the force-displacement data using the equation

$$Force (N) = A * (e^{B * Displacement (mm)} - 1)$$

Equation 1

where A and B were numerically optimized using MATLAB 2010a (MathWorks, Natick, MA). The toe region was defined as the portion of the force deflection curve between 1.25% and 2.5% compression. The elastic region was defined as the portion of the force deflection curve between 2.5% and 5% compression. Both the toe region and elastic region stiffness were calculated from linear fit of the force-displacement curve within the respective region. For tests that were stopped by the force interlocks at 500N, the stiffnesses were calculated from extrapolated non-linear regressions (Equation 1). The hysteresis energy was calculated as the difference in mechanical work between the loading and unloading phase.

Statistical analysis was performed using SAS v9.3 (SAS Institute, Cary, NC) with a significance level of $p < 0.05$. Linear mixed models (PROC MIXED) were used to examine the ability of the anthropometric and testing parameters (independent variables) to predict toe region stiffness, elastic region stiffness, and hysteresis. The parameters investigated were age, compression direction, normalized deflection rate, head length, head width, head circumference, occipital skull thickness, and frontal skull thickness. First, the correlation of the anthropometric parameters with respect to age and one another was calculated. If anthropometric parameters were significantly and highly correlated with age, they were left out of the linear mixed models. Mixed models were used to account for the repeated nature of the testing, with each specimen generally undergoing eight compression tests (two directions with four loading rates per direction). Backwards selection was used to determine the most parsimonious model, with likelihood ratio tests used to determine if the more parsimonious model provided a statistically different fit from the parent model.

Results

Examples of the force-displacement curves and the non-linear fits are shown in Figure 2. The stiffness values for all directions and rates are summarized in Figure 3, while the coefficients for the exponential fits are given in Table 3. The average R^2 for the non-linear fits across all specimens was 0.996, with the lowest value being 0.979. Out of the 160 stiffnesses, 17 were calculated using the nonlinear curve fit (Table 3) because the 500N force interlock was triggered; only one toe region stiffness was calculated using the non-linear curve fit (P21F). Seven AP compression tests could not be run due to difficulties in compressing the heads in the AP direction (P18M, P21F).

The Pearson correlation coefficients from the correlation analysis between age and the anthropometric variables were found to be significant ($p < 0.05$) for all anthropometric variables, thus rejecting the null hypothesis of no correlation between the two variables in question. The lowest correlation was found between age (in months) and head width ($r = 0.71$), while the highest correlations were found between circumference and head width, and between circumference and head length ($r = 0.98$ for both). Therefore, all anthropometric variables were deemed highly correlated with age and not included as predictors in the regression models.

In general, toe region stiffness, elastic region stiffness, and hysteresis were best predicted by the most parsimonious model that used only age as a predictor. Neither the direction nor rate of compression were statistically significant predictors. All of the regression parameter estimates are shown in Table 4. More specific results are given below.

Toe Region Stiffness

The linear mixed model showed that toe region stiffness was strongly dependent on age ($p < 0.0001$). Neither the direction of compression ($p = 0.65$) nor deflection rate

($p=0.24$) were significant predictors of toe region stiffness; however, at higher deflection rates the heads were qualitatively more stiff than at lower rates (Table 2). The likelihood ratio test illustrated that the more parsimonious model including only age as a predictor was significantly different from the parent model ($p<0.0001$). The average toe region stiffnesses across both directions and deflection rates were 1 N/mm, 11 N/mm, 40 N/mm, and 873 N/mm for the premature, neonatal, infant, and youth heads.

Elastic Region Stiffness

Like toe region stiffness, the linear mixed model showed that age was the only significant predictor of elastic region stiffness ($p<0.0001$). Neither direction ($p=0.08$) nor deflection rate ($p=0.28$) were significant predictors. However, under compression in the AP direction, the heads were qualitatively stiffer than under compression in the lateral direction (Table 2). The likelihood ratio test again illustrated that the more parsimonious model including only age as a predictor was significantly different from the parent model ($p<0.0001$). The average elastic region stiffnesses across both directions and deflection rates were 1.5 N/m, 20.6 N/mm, 91 N/mm, and 2581 N/mm for the premature, neonatal, infant, and youth heads.

Head Hysteresis

Once again, the linear mixed model illustrated that age was the only significant predictor of hysteresis ($p=0.04$), while direction ($p=0.56$) and deflection rate ($p=0.11$) were not. Again, the likelihood ratio test illustrated that the model including only age as a predictor was significantly different from the parent model ($p=0.05$). While the effect of age is significant, it does not appear to be particularly large (Figure 6). The average hysteresis across both directions and all deflection rates were 49%, 47%, 45%, and 52% for the premature, neonatal, infant, and youth heads.

Discussion

Previous studies of the head in compression have loaded adult heads to the point of fracture (McElhaney, 1976; McElhaney et al., 1972; Yoganandan et al., 1995). There are only two previous studies of the pediatric head in compression (Cohnstein, 1875; Prange et al., 2004). Cohnstein investigated compression due to application of forceps but did not report any forces, and Prange investigated only a small sample of neonatal heads. The current study provides quantitative compressive stiffness measurements of the human pediatric head that have been heretofore unavailable.

Limitations

The first limitation of this study is the small number of pediatric heads included. The small number is due to the extreme difficulty in obtaining pediatric tissue donations. The included specimens were obtained over a twenty year period and represent the largest such collection ever studied. The specimens were double bagged and frozen at -20°C to limit the effects of the long-term storage. The second limitation of this study was that the heads were compressed at relatively low loads to ensure that no fractures would occur. The force interlocks resulted in inconsistent normalized compressive displacements in some cases, which prevents direct comparison across all specimens without the use of non-linear curve fits (Equation 1). A third limitation is the boundary condition used during the head compression test. Saline-soaked gauze was used to loosely cover the foramen magnum, allowing unconstrained expansion of the intracranial contents (Thomas, Sezgin et al. 1968, Prange, Luck et al. 2004). A fourth limitation was the difficulty in compressing the heads in the AP direction. Polished plates were used to create boundary conditions that are relatively easy to model mathematically; however, the lack of friction combined with the shape of the older heads resulted in insufficient constraints for some

specimens when loading in the AP direction (P18M, P21F). A fifth limitation was that the compression tests were not randomized. This was done to prevent unintentionally fracturing the specimen during the higher rate test and rendering the specimen unfit for testing at the lower rates. Therefore, the results for the higher deflection rates may be affected by the prior tests at lower rates.

Effect of Age

Age had the greatest effect on the toe region stiffness, the elastic region stiffness, and the hysteresis of the pediatric head. McElhaney showed the average adult AP and lateral stiffnesses to be 2450 N/mm and 1225 N/mm (McElhaney, 1976; McElhaney et al., 1972), respectively. This was less than the stiffnesses of the 16 year old specimen, but considerably more than the stiffnesses of the 9 year old. The mean stiffnesses of the neonatal group were 2 orders of magnitude less than those of the youth group.

The reasons for the stiffness changes are both mechanical and anatomical, and are consistent with the developmental changes in the skull that have been described in the literature. During both the premature and neonatal periods, the head is composed of regions of compliant tissue (fontanelles) and sutures (Agur and Lee, 1991). These regions allow head deformation permitting easier passage through the birth canal (Lapeer and Prager, 2001). From premature to neonate age, the bones of the head begin to thicken and ossify (O'Connor et al., 2010; Sims and Baron, 2000). From the neonatal to infant ages, the head sutures begin to fuse (rigidly connect) and are able to support a bending moment by 6 months of age (Bradley et al., 1996; Cohen, 2000; Kuffel, 2004). The posterior and anterior fontanelles close on average at 2 months and 13.8 months of age (Cohen, 2000; Kuffel, 2004). The closing of the sutures adds rigidity and stiffness to the head. From the infant ages to the youth ages, the fontanelles and

sutures close (connect) and begin interdigitating (forming interlocking finger-like connections of bone). The bone continues to thicken and transitions from a single-layer to a tri-layer structure (Davis et al., 2012; Faiz et al., 2011; White and Folkens, 1999). Lastly, the bone thickens to a final thickness ranging between 4.0mm and 7.4mm, and interdigitation continues into adulthood (Getz, 1960; Ishida and Dodo, 1990). Each phase of head growth adds rigidity to the head, which is reflected in the stiffness results presented here (Figure 5 and Table 2).

Effect of Compression Direction and Deflection Rate

Neither compression direction nor deflection rate were found to be statistically significant predictors of toe region stiffness, elastic region stiffness, or hysteresis in this study. However, this may have been due to a lack of statistical power. Prior studies of adults have found the AP direction to be significantly stiffer than the lateral direction. In our sample of neonates, the opposite may be true for the elastic region. As a neonate, the cranial bones are more curved, and the head is more spherical than as an adult (Silau et al., 1995). These factors may produce similar stiffness values across different directions, a plausible consequence of the birth process, since the head is compressed in multiple directions during birth (Hodgson et al., 1967; Thomas et al., 1968). The 16-year-old youth specimen was stiffer in the AP direction, similar to adult heads.

Increasing the deflection rate generally increased the stiffness across all age groups for both the toe region and elastic region stiffness. However, this increase was not statistically significant, which is an unexpected result for viscoelastic biological tissues. This finding is likely due to a lack of statistical power. The expected rate dependence is attributable to both the skin, which has been shown to be viscoelastic, and the suture and fontanelle, which may also be rate dependent (Agache et al., 1980; Coats and Margulies, 2006; Silver et al., 2002).

Pediatric Head Response and Child Birth

No fractures were observed from the compression of the neonate heads. This is consistent with the clinical experience that during a typical childbirth, skull fractures are highly unusual. A study conducted by Rubin in the 1960s showed that one skull fracture occurred for 15,435 normal births (Rubin, 1964).

Despite the limitations of sample size (discussed above), a number of conclusions can be drawn from this data. Age was found to be the only significant predictor of head stiffness. The stiffness of the head increases by as much as 2 to 3 orders of magnitude with maturation from neonate to 16 years old. Across all ages, the stiffness of the head increased with deflection rate; however, this increase was not statistically significant. The quantitative biomechanical data for the pediatric head presented here is the first such collection of its kind, and can be used in the development and validation of physical and computational models of the pediatric head.

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Figures

Figure 1: The head was placed between two platens and the MTS ram's upward motion was used to compress the head. The left image shows the anterior-posterior compression test setup while the right displays the lateral compression test setup. The ATD head is used to demonstrate how the human head was positioned between the compression platens.

Figure 2: Example of a complete loading cycle with its non-linear fits showing the toe region and the elastic region stiffnesses (left). Examples of quasi-static force-curves from each of the four developmental age groups (right). The left graph is for the anterior-posterior compression of the neonate, P08M (neonate). The right figure is for the lateral quasi-static compression of the P02F, P05F (1-day-old), P12M (5-month-old), and P18M (9-year-old). The 9-year-old hit the interlocks at 500N.

Figure 3: A summary plot of all the toe and elastic region stiffness values for every age, direction, and rate. Note the log scale. The linear mixed models showed that the toe region stiffness and elastic region stiffness were only significantly dependent on age and not direction or deflection rate ($p < 0.05$).

Figure 4: Model results for the toe region stiffness. The most parsimonious model is shown along with all of the data for the 4 rates and 2 loading directions. The dotted lines are the confidence intervals. A zoomed in plot is on the right. Only age was a significant predictor and not direction nor deflection rate ($p < 0.05$).

Figure 5: Model results for the elastic region stiffness. The most parsimonious model is shown along with all of the data for the 4 rates and 2 loading directions. The dotted lines are the confidence intervals. A zoomed in plot is on the right. Only age was a significant predictor and not direction nor deflection rate ($p < 0.05$).

Figure 6: Model results for hysteresis. The most parsimonious model is shown along with all of the data for the 4 rates and 2 loading directions. The dotted lines are the confidence intervals.

Appendix A

Figure A1: Exemplar force displacement plots with linear fits. The figure on the left is for the 5-month-old for the 0.3/s test in the anterior-posterior direction and the figure on the right is for the 9-month-old for the 0.3/s test in the anterior-posterior direction.

Figure A2: Exemplar force displacement plots with linear fits. The figure on the top left is for the 0.1/s anterior-posterior tests for the 11-month-old. The figure on the top right is for the 0.1/s lateral tests for the 9-year-old. The bottom figure is for the quasi-static lateral test for the 16-year-old. The 9-year-old and 16-year-old figures show only the small compression stiffness.

Appendix B

Figure B1: Exemplar force displacement plots. The figure on the left is for the 5-month-old for the 0.3/s test in the anterior-posterior direction and the figure on the right is for the 9-month-old for the 0.3/s test in the anterior-posterior direction. The remaining exemplar plots can be found in (Loyd, 2011).

Figure B2: Exemplar force displacement plots. The figure on the top left is for the 0.1/s anterior-posterior tests for the 11-month-old. The figure on the top right is for the 0.1/s lateral tests for the 9-year-old. The bottom figure is for the quasi-static lateral test for the 16-year-old. The remaining exemplar plots can be found in (Loyd, 2011).

Tables

Table 1: Specimen Data. The ages are referenced from 40-weeks-gestation.

ID	Age (mo.)	Age	Sex	Age Group	Race	Head Length (cm)	Head Width (cm)	Head Circ. (cm)	Skull Frontal (mm)	Skull Occiput (mm)	Cause of death
P02F	-4.5	20-wk. gest.	F	Premature	Caucasian	7.1	5.9				Heart Failure
P07M	-1.6	33-wk-gest.	F	Neonate	Unknown	9.9	8.4	29.6	2.1	3.1	Unknown
P13F	-1.4	34-wk-gest.	F	Neonate	Unknown	10.7	7.2	29.7	2.8	2.8	Unknown
P08M	-0.6	37.5 wk-gest.	M	Neonate	Caucasian	12.6	9.6	35.8	2.2	3.2	Pulmonary hypoplasia
P05F	0.0	1-day	F	Neonate	Caucasian	10.8	9.0	33.4	2.3	2.8	Diaphragmatic hernia
P03M	0.1	3-day	M	Neonate	Caucasian	10.3	8.5	30.4	2.3	1.6	Ischemic encephalopathy; cerebral infarction
P06F	0.4	11-day	F	Neonate	Black	10.8	9.5	34.8	2.0	2.5	Non-immune hydrops fetalis; intercranial hemorrhage
P12M	5.0	5-months	M	Infant	Black	13.1	10.9	40.8	2.9	3.1	Respiratory failure
P14M	9.5	9-months	M	Infant	Black	14.8	12.0	46.5	4.1	5.0	Chronic obstructive pulmonary disease
P15F	11.5	11-months	F	Infant	Caucasian	14.8	12.2	44.5	4.7	4.0	SIDS, renal failure
P18M	108.5	9-years	M	Youth	Black	16.9	13.0	49.3	6.5	6.9	End stage renal disease; secondary: hyperkalemia
P21F	192.5	16-years	F	Youth	Caucasian	19.2	14.5	56.6	7.9	13.1	Seizure disorder

Table 2: Linear toe and elastic region stiffness values (N/mm) for all specimens, all directions, and all deflection rates. The bold lines separate age groups and the gray cells are data not reported due to problems with the test. AP stands for anterior-posterior direction.

Specimen	Age	Region	0.0005/s		0.01/s		0.1/s		0.3/s	
			AP	Lateral	AP	Lateral	AP	Lateral	AP	Lateral
P02F	-4.5	Toe	0.87	1.01	0.71	0.75	0.74	0.79	0.81	0.87
		Elastic	0.93	1.96	0.99	1.10	1.14	1.53	1.30	2.68
P07M	-1.6	Toe	10.3	11.5	17.7		19.3			
		Elastic	12.1	15.0	22.9		27.5			
P13F	-1.4	Toe	7.8	5.8	9.1	10.2	12.0	13.3	14.2	16.7
		Elastic	9.4	9.3	16.3	21.7	21.7	28.2	24.1	33.4*
P08M	-0.5	Toe	2.8	4.7	6.0	6.2	7.7	8.5	9.6	10.4
		Elastic	4.4	8.1	10.9	19.6	14.2	27.4	16.1*	29.2*
P05F	0.0	Toe	7.1	4.2	8.3	8.8	9.9	11.3	12.3	15.0
		Elastic	9.7	6.8	13.5	21.1	15.8	25.3	17.3*	28.5*
P03M	0.1	Toe	3.7	7.5	14.2	14.9	15.8	19.0	20.7	25.4
		Elastic	5.7	9.8	26.9	34.1	35.1	43.6	46.3*	47.2*
P06M	0.4	Toe	3.4	6.1	12.9	9.1	11.2	15.5		
		Elastic	5.4	7.6*	22.1	21.5	23.7	35.2		
P12M	5.0	Toe	35.7	22.2	32.2	26.3	36.8	30.7	41.0	37.9
		Elastic	36.8	41.7	57.7	53.4	66.6	61.7	72.3	66.8
P14M	9.5	Toe	24.8	17.8	19.2	18.5	28.5	28.1	32.1	32.2
		Elastic	39.5	37.4	54.5	53.5	76.0	74.9	83.6	75.4
P15F	11.5	Toe	65	34	59	36	90	44	110	47
		Elastic	138	66	203	79	249	95	306	99
P18M#	108.5	Toe		188		393*		582*		541*
		Elastic		812*						
P21F#	192.5	Toe	166	318*		1918*		2207*		1989*
		Elastic	4776*	3924*						

* denotes that the stiffness was calculated using the non-linear curve fit.

Specimens P21 and P18 were unstable in the test device, meaning that they rotated in response to AP compression.

Table 3: The coefficients A and B for the non-linear fits of the force-deflection data using Equation 1. AP stands for anterior-posterior direction.

Specimen	Fit Coeffs.	0.0005/s		0.01/s		0.1/s		0.3/s	
		AP	Lateral	AP	Lateral	AP	Lateral	AP	Lateral
P02F	A	10.38		1.93	0.25	1.60	0.30	2.02	0.90
	B	0.08		0.24	0.73	0.29	0.74	0.29	0.59
P03M	A	9.00	17.90	22.00	16.20	17.20	20.00	20.00	30.60
	B	0.25	0.25	0.34	0.45	0.41	0.46	0.43	0.41
P05F	A	16.20	8.20	20.60	6.30	28.90	9.00	44.30	14.30
	B	0.25	0.30	0.25	0.53	0.23	0.50	0.19	0.44
P06M	A	4.60	24.30	27.70	7.60	14.40	15.40		
	B	0.32	0.17	0.27	0.49	0.37	0.45		
P07M	A	26.31	53.36	93.45		73.86			
	B	0.22	0.17	0.14		0.19			
P08M	A	13.84	5.95	9.40	3.58	13.95	4.98	22.50	7.24
	B	0.15	0.36	0.29	0.60	0.27	0.60	0.23	0.54
P13F	A	29.51	10.29	15.68	9.09	22.32	12.16	29.47	18.92
	B	0.17	0.35	0.30	0.54	0.29	0.53	0.27	0.48
P12M	A	101.04	29.42	46.39	35.30	56.27	44.76	61.74	68.39
	B	0.17	0.35	0.29	0.35	0.29	0.34	0.29	0.30
P14M	A	47.44	19.58	20.58	11.94	36.17	21.66	39.24	24.51
	B	0.23	0.36	0.34	0.47	0.31	0.44	0.32	0.43
P15F	A	67.76	40.29	30.64	41.06	67.79	57.14	75.90	73.34
	B	0.32	0.34	0.47	0.36	0.39	0.34	0.40	0.32
P18M	A		72.32		9.78		20.86		61.82
	B		0.58		1.34		1.23		0.90
P21F	A	6.72	32.84		9.99		21.26		41.25
	B	0.91	0.88		1.71		1.53		1.31

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Table 4: Parameter estimates for backwards-selected regression models.

Independent Variable	Term	Estimate	Standard Error	t Value	p
Toe Region Stiffness (N/mm)	Intercept	5.8124	6.6532	0.87	0.4028
	Age (Months)	6.1621	0.3354	18.37	<0.0001
Elastic Region Stiffness (N/mm)	Intercept	-45.3573	140.1200	-0.32	0.7528
	Age (Months)	19.3107	2.2115	8.73	<0.0001
Hysteresis	Intercept	0.4597	0.0098	46.75	<0.0001
	Age (Months)	0.0004	0.0002	2.32	0.0426

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Figures

Figure 1: The head was placed between two platens and the MTS ram's upward motion was used to compress the head. The left image shows the anterior-posterior compression test setup while the right displays the lateral compression test setup. The ATD head is used to demonstrate how the human head was positioned between the compression platens.

Figure 2: Example of a complete loading cycle with its non-linear fits showing the toe region and the elastic region stiffnesses (left). Examples of quasi-static force-curves from each of the four developmental age groups (right). The left graph is for the anterior-posterior compression of the neonate, P08M (neonate). The right figure is for the lateral quasi-static compression of the P02F, P05F (1-day-old), P12M (5-month-old), and P18M (9-year-old). The 9-year-old hit the interlocks at 500N.

Figure 3: A summary plot of all the toe and elastic region stiffness values for every age, direction, and rate. Note the log scale. The linear mixed models showed that the toe region stiffness and elastic region stiffness were only significantly dependent on age and not direction or deflection rate ($p < 0.05$).

Figure 4: Model results for the toe region stiffness. The most parsimonious model is shown along with all of the data for the 4 rates and 2 loading directions. The dotted lines are the confidence intervals. A zoomed in plot is on the right. Only age was a significant predictor and not direction nor deflection rate ($p < 0.05$).

Figure 5: Model results for the elastic region stiffness. The most parsimonious model is shown along with all of the data for the 4 rates and 2 loading directions. The dotted lines are the confidence intervals. A zoomed in plot is on the right. Only age was a significant predictor and not direction nor deflection rate ($p < 0.05$).

Figure 6: Model results for hysteresis. The most parsimonious model is shown along with all of the data for the 4 rates and 2 loading directions. The dotted lines are the confidence intervals.

Appendix A

Figure A1: Exemplar force displacement plots with linear fits. The figure on the left is for the 5-month-old for the 0.3/s test in the anterior-posterior direction and the figure on the right is for the 9-month-old for the 0.3/s test in the anterior-posterior direction.

Figure A2: Exemplar force displacement plots with linear fits. The figure on the top left is for the 0.1/s anterior-posterior tests for the 11-month-old. The figure on the top right is for the 0.1/s lateral tests for the 9-year-old. The bottom figure is for the quasi-static lateral test for the 16-year-old. The 9-year-old and 16-year-old figures show only the small compression stiffness.

Appendix B

Figure B1: Exemplar force displacement plots. The figure on the left is for the 5-month-old for the 0.3/s test in the anterior-posterior direction and the figure on the right is for the 9-month-old for the 0.3/s test in the anterior-posterior direction. The remaining exemplar plots can be found in (Loyd, 2011).

Figure B2: Exemplar force displacement plots. The figure on the top left is for the 0.1/s anterior-posterior tests for the 11-month-old. The figure on the top right is for the 0.1/s lateral tests for the 9-year-old. The bottom figure is for the quasi-static lateral test for the 16-year-old. The remaining exemplar plots can be found in (Loyd, 2011).