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Pediatric Tensile Neck Strength Characteristics Using a Caprine Model

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ABSTRACT

The purpose of this study was to determine neck strength characteristics of children indirectly using scaling relationships through a caprine animal model. Because of the necessity to evaluate airbag designs for injury risk to the out-of-position child, a strong foundation of experimental data is needed to obtain appropriate tolerance values. Cadaver goat cervical spines of different ages were tested mechanically in non-destructive bending and destructive tensile modes. Injuries induced in destructive testing such as endplate failure and ligament tears are consistent with clinical observations. Specimens demonstrated increased strength characteristics with age. Stiffness and tensile strength increased with cervical level and with age. Scaling relationships were developed with respect to the adult specimens. Results indicated that currently used scaling relationships may require more conservative strength limits for children of one and three years of age.

INTRODUCTION

The use of airbag technology in vehicles has proved beneficial to the general public. Their widespread use has also increased reports of injuries related to their deployment. While the majority of these injuries have been minor, the exposure of children to airbag deployment has resulted in more serious injuries (Winston, 1996). In many cases, adult occupants sustained little or no injury while child passenger injuries resulted in severe injury or death. The mechanism of the injuries has been primarily attributed to tensile loading as the airbag unfolds under the chin of the child.

Obtaining tolerance values for children of different age groups can help mitigate these injuries. Determination of these data for children is difficult because tissue for these tests is not readily available. Through the use of animal models, scaling factors determining the relationship between developmental age group strengths can be tested and related to human age group tolerance.

METHODS

The tensile neck strength and material characteristics of the pediatric cervical spine were studied using a caprine (goat) cadaver model. Caprine spinal column tissues were obtained from an ongoing study utilizing the lumbar spine section of these animals. The bone growth and structural component similarities were used to evaluate the skeletal equivalent maturation stage of the goat specimens. The human age equivalent to the one-year-old, three-year-old, six-year-old, twelve-year-old, and adult age groups was determined using CT images. Briefly, age equivalence was determined by the number of ossification sites during the stages of skeletal maturation. Our previous work in this area describes this process in more detail (Kumaresan et al., 2000). Twenty-five specimens of varying age and size were tested resulting in 19 full vertebral sections and 85 motion segments.

Several different load tests were performed on each specimen in each age group. Each specimen was initially tested under sub-failure loads in tension and load relaxation from the head to C6. The spinal segment was then sectioned into OC-C2, C3-C4, C5-C6, and C7-T1 motion segments. These segments were tested in the same sub-failure in axial tension and load relaxation tests. Pure moment in bending for flexion-extension and lateral bending, and failure in axial tension were then tested on the motion segments. Preparation of the desired vertebrae required dissection of the segments and the addition of mounted interface plates. The segments were mounted by passing wires over the vertebrae pedicles and through the vertebral bodies (FIG. 1). The vertebrae and wire composite were mounted in PMMA (dental acrylic), creating an interface for the piston and load cells. Some muscle was left intact along with gauze soaked in Ringer's solution to preserve the fluid in the specimen and the integrity of the intervertebral joints. Reflective targets were placed in the mounting plates for tracking with video analysis to determine the movement of the specimen during the load tests.

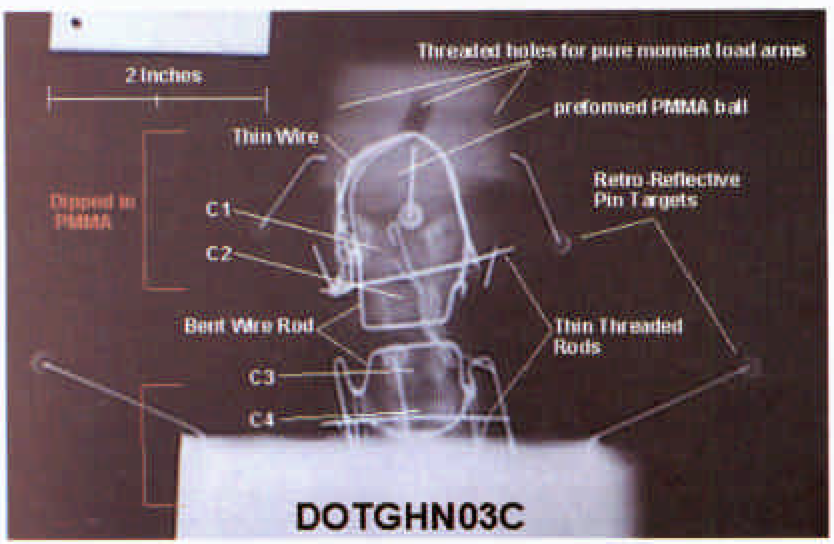

FIG. 1. A-P x-ray of a mounted motion segment with mounting plates, reflective targets, and mounting wires.

Axial testing of the cervical spine was done with an electro-hydraulic piston (MTS, Minneapolis, MN). The computer-controlled system was programmed under force control for the distraction tests. An estimation of 20% of failure strength was used as a sub-failure testing limit. The force ramped to this level at a quasi-static rate and back to zero. Load relaxation was accomplished by distracting the specimen to the sub-failure limit and maintaining that distraction level for three minutes. An inferior six-axis load cell, superior axial load cell, and Piston LVDT provided measurements for all reactions of the system in the distraction testing.

Pure moment testing utilized a four-camera, three-dimensional motion analysis system (Motion Analysis Corporation, Santa Rosa, CA). This system allows the movement of the specimen to be tracked in three dimensions. From these measurements, Euler rotations were calculated showing the rotation in the direction of force application as well as the off-axis directions. A pure moment was created with masses hung from a pulley system (FIG. 2). This system applied torque to the top of the specimen preparation through load arms. Up to five load steps were used to derive the moment-rotation response. A bottom six-axis load cell measured the reaction forces and moments of the specimen to ensure pure moment loading.

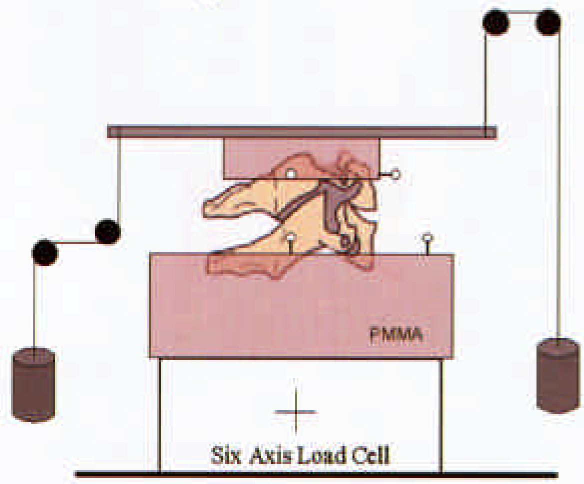

FIG. 2. Pure moment testing diagram showing load cell and moment application pulleys and weights.

RESULTS

From the specimen mechanical testing, several individual scaled relationships were developed. Measurements of linear and rotational stiffness, load relaxation rate, and destructive failure force in tension were taken for comparison. Distraction testing in the piston setup resulted in force-deflection relationships. Stiffness was calculated as the slope of the most linear portion of the load-displacement curve within the physiologic loading range. FIG. 3 gives the resulting linear stiffness values under tensile loading for each age group.

Stiffness values were also calculated from the moment-rotation response curves. For each segment and age group the stiffness was averaged. In this preliminary analysis, rotational stiffness as a function of spinal level was assumed to be fairly constant and, therefore, the results were averaged together for all spinal levels. Scale factors were derived for each age group assuming the adult values to be on unity (FIG. 4).

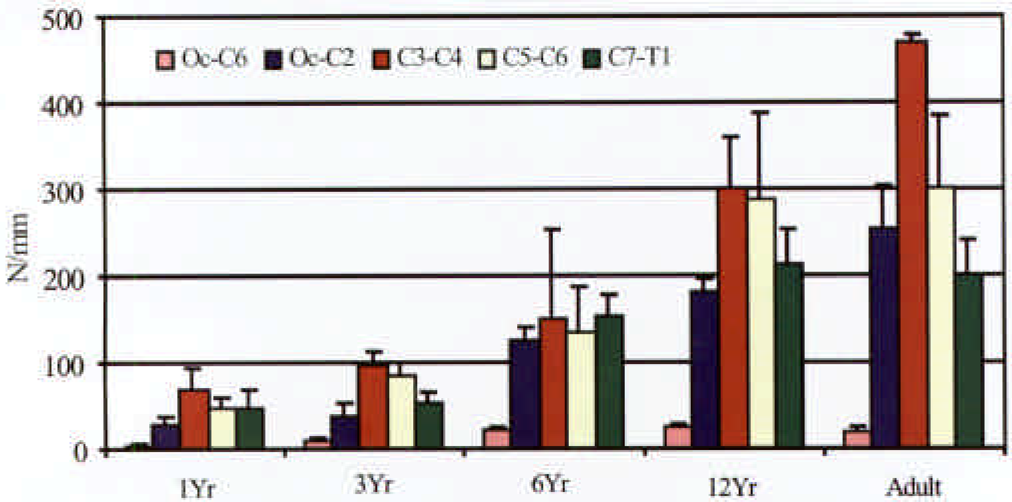

FIG. 3. Linear stiffness averages for the age groups and motion segments taken from the force displacement measurements of the distraction testing.

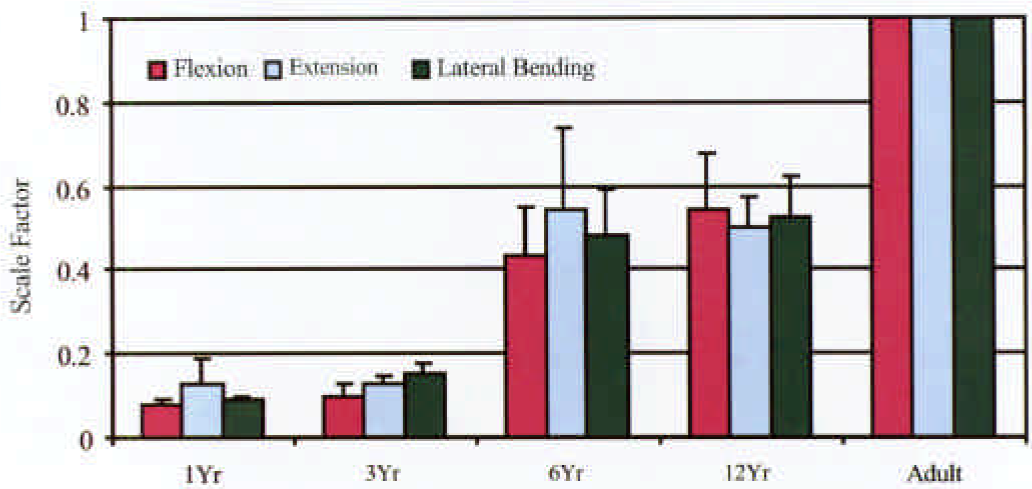

FIG. 4. Average scaling factors derived from pure moment bending tests for all motion segments tested in this loading mode.

Tensile failure tests were conducted for motion segments: OC-C2, C3-C4, C5-C6, and C7-T1. The force at failure values ranged from 89N to 3720N. The resulting averages and standard deviations are shown in FIG. 5. The force increases with age and in the 12-year-old and adult age groups the force is higher in the upper cervical segment.

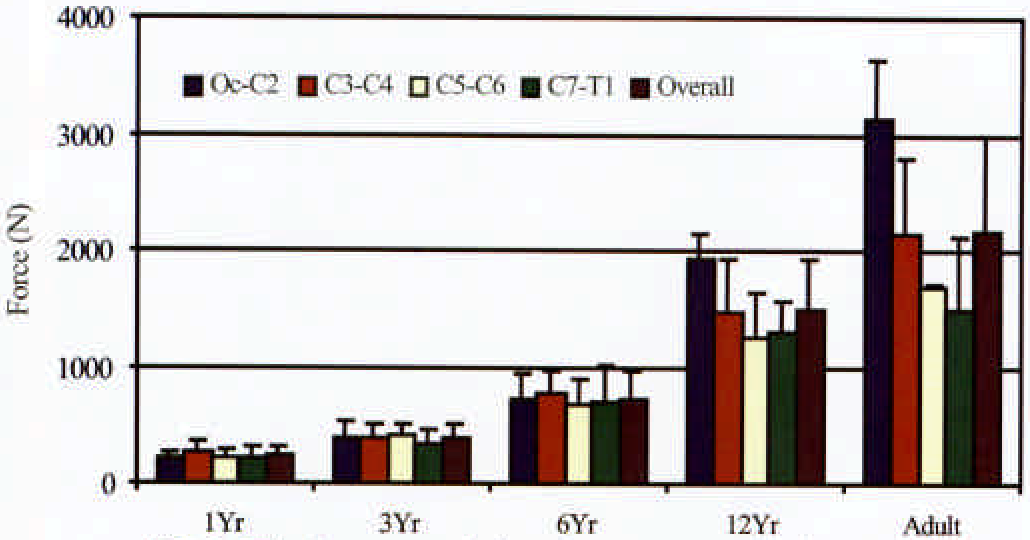

FIG. 5. Failure force averages for the motion segments tested in distraction.

DISCUSSION

Currently available neck strength tolerance levels for children and infants have been derived using scaling methods (Yoganandan et al., 1996; Melvin, 1995). Isolated tissue tests (e.g., calcaneal tendon) on pediatric specimens of different ages were used as a starting point to obtain ratios between age groups. Studies that used three-year-old equivalent porcine preparations exposed to airbag deployment have formed the basis for the three-year-old human neck tensile tolerance (Mertz et al., 1986; Prasad and Daniel, 1984). The tolerance for other child ages was derived using the three-year-old data as a basis, and scaling up or down using calculated ratios from tissue specimen tests (Yoganandan et al., 1996; Melvin, 1995).

This is the first study of its kind to derive the tolerance values directly using age-equivalent animal cervical spine specimens. The age-equivalence was determined using spinal structural maturation. The young goat neck structural anatomy progresses in the same sequence as the human. The timing, however, is different in that the animal develops more rapidly than the human. For example, a newborn goat was at the same skeletal maturity stage as a one-year-old human, and a six-week-old goat was equivalent to a three-year-old human. The caprine model has also been validated for use in cervical spinal surgery studies (Pintar et al., 1994; Zdeblick et al., 1993). Despite its quadruped nature, the goat holds its head upright throughout life, thereby axially loading the cervical spine like in the human condition. The size of the goat vertebrae are roughly the same or larger than human vertebrae and have the same anatomic features including intervertebral disc anulus and nucleus, facet joints, and spinous processes. All of these structural similarities render the goat cervical spine a good human surrogate.

Results from these studies demonstrate that currently used scaling ratios between ages are close to what was derived in the current study. The main finding, however, is that the tolerance values for the one- and three-year-old may need more conservative values. Another animal model that would conduct the same evaluations would provide additional confidence in these values. The use of tolerance data in the configuration of child and infant crash test dummies can create a more realistic estimate of injury. Determination of injury probability can then lead to safer and stronger designs.

ACKNOWLEDGEMENTS

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