PEDIATRIC AND SMALL FEMALE NECK INJURY SCALE FACTORS AND TOLERANCE BASED ON HUMAN SPINE BIOMECHANICAL CHARACTERISTICS

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ABSTRACT

Existing neck scale factors to determine injury assessment reference values for the pediatric one, three and six year old, and the 5th percentile female populations are based on extrapolations from the adult 50th percentile male and tensile strength data from the calcaneal tendon. The research question addressed in this study is as follows. What are the scale factors and resulting neck tolerances for these age-specific populations if data from human spinal components and neck geometry are used? The analysis included the determination of scale factors under extension, tension, compression, and flexion loading modes as a function of age, i.e., one, three and six year old, and the 5th percentile female groups. Variations in the biomechanical properties of each spinal component (e.g., vertebra, disc, ligament, cartilage, muscle, spinal cord) were determined from human cadaver studies. Active spinal components were identified under each of the four loading modes and relationships were established for each component to obtain material-based scale factors. Combining material scaling with neck geometrical data yielded the scale factors for the one, three, and six year old under extension, tension, compression, and flexion loading modes. The age-dependent scale factors in extension, tension, compression, and flexion were: 0.14, 0.25, 0.24, 0.14 for the one year old, 0.19, 0.30, 0.29, 0.18 for the three year old, and 0.25, 0.37, 0.36, 0.24 for the six year old, respectively. The adult 50th percentile male factors were considered to be unit values under each loading mode. Tolerance values (critical intercept values for the N_{ij} criteria) were compared with the data obtained using scale factors from the calcaneal tendon. Scale factors, and hence, resulting injury tolerance values based on spine component material properties, are more appropriate than the values extrapolated from the calcaneal tendon tensile test data.

Key Words: Biomechanics, neck, injury criteria, pediatrics, tolerance

HUMAN TOLERANCE to mechanically induced injury is dependent on factors such as age and gender. With particular reference to neck tissues, because of their unique anatomical and developmental characteristics, direct extrapolations are not fully appropriate from one age group and/or gender to another domain. For example, changes in the ossification patterns even among the various cervical vertebrae, and the development of the uncinate and uncovertebral anatomy as a consequence of the secondary ossification process, contribute to widely varying age-dependent biomechanical responses and, hence, tolerance (Kumaresan et al., 1997). The majority of biomechanical tolerance data have been extracted from adult human cadaver experiments. Presently, a paucity of age-specific experimental data exists on neck tissues. This includes the isolated spinal component (e.g., ligaments) and spinal column (segmented or entire) evaluations. However, of necessity, vehicular interior surfaces are routinely designed and evaluated for neck injury mitigation using "scaled" tolerance data. With reference to the pediatric age group, the following method has been adopted.

Development of the collagen tissue of the calcaneal tendon was assumed to be similar to the development of neck ligaments (Melvin, 1995). The ultimate failure stress (strength), ultimate stiffness, and ultimate elongation data for the human calcaneal tendon were extracted from studies conducted in Japan (Yamada, 1970). Using dimensional-analysis techniques, the calcaneal tendon strength data were combined with neck circumference anthropometry to determine scale factors as a function of age.

A principal reason to adopt calcaneal tendon data in order to determine scale factors was the lack of material property information as a function of age for human neck components. It is well known that the soft tissues (ligaments, annulus fibers, facet joints, etc.) of the neck structure are not identical in terms of growth and development, and their material properties are not identical to the calcaneal tendon. Furthermore, differences exist in the mechanical properties even among different cervical spine ligaments (Yoganandan et al., 1998). In addition, maturation of the disc in terms of stiffness and fiber density, and orientation of the facet joint anatomy non-uniformly change with respect to age and do not parallel the calcaneal tendon structure (Yoganandan et al., 2000). It is, therefore, reasonable to expect that more appropriate scale factors can be derived if they are based on the properties of the various constituents of the neck structures instead of a single, and most distally located, calcaneal tendon. This was the objective of the present study.

METHODS

Human neck structures resist compression, tension and shear forces, flexion-extension, and torsion and lateral bending moments. Depending on the nature of the external load vector, combinations of forces and moments are possible. Different components internally act to resist the external load. For example, under extension-bending moment, the anterior longitudinal ligament always resists the load by distraction. The contributing elements for resisting the external load, in general, are the cartilages, intervertebral discs, ligaments, vertebrae, spinal cord, and muscles. Age-dependent properties were obtained for the above components of the human neck structures. Both linear and polynomial regression fit for experimental data were attempted, and the fit that provided the strongest coefficient of variation was used to express the age-dependent relationship. Twenty-five years of age was

used to represent adult skeletal maturity (Clark et al., 1998). Scale factors were derived for different age groups by appropriately combining these properties with neck geometry using the principles of dimensional analysis (Kleinberger et al., 1998; Melvin, 1995).

Cartilage: The pediatric cervical column is replete with cartilages, particularly in the early years of human life. The first cervical vertebra has three ossification centers while the axis has five centers. The remaining typical cervical vertebrae have three centers. These centers contribute to the bilateral neurocentral synchondrosis and posterior synchondrosis which consists of cartilage (Bardeen, 1970). Growth plates are made of cartilage and, with advancing age, these cartilages gradually transform into osseous structures (Bailey, 1952). Therefore, in order to account for the contribution of the cartilage component (not present in the calcaneal tendon) in resisting the external load, it is necessary to incorporate its compressive and tensile properties. As a first step, since pediatric human cartilage experimental data are not presently available, information from the testing of hyaline cartilage was used. Using published data, the following equation relating failure elongation (Y) to age (A) was derived to determine the scale factors under compression (equation 1) and tension (equation 2). Scaling factors for the one, three and six year old, expressed as a percentage of the adult, are shown in figure 1 (Ko & Takigawa, 1953; Yokoo, 1952).

$$Y=20.21-0.25*A+20E-4*A^2 \quad (1)$$
$$Y=31.58-0.15*A-22E-4*A^2 \quad (2)$$

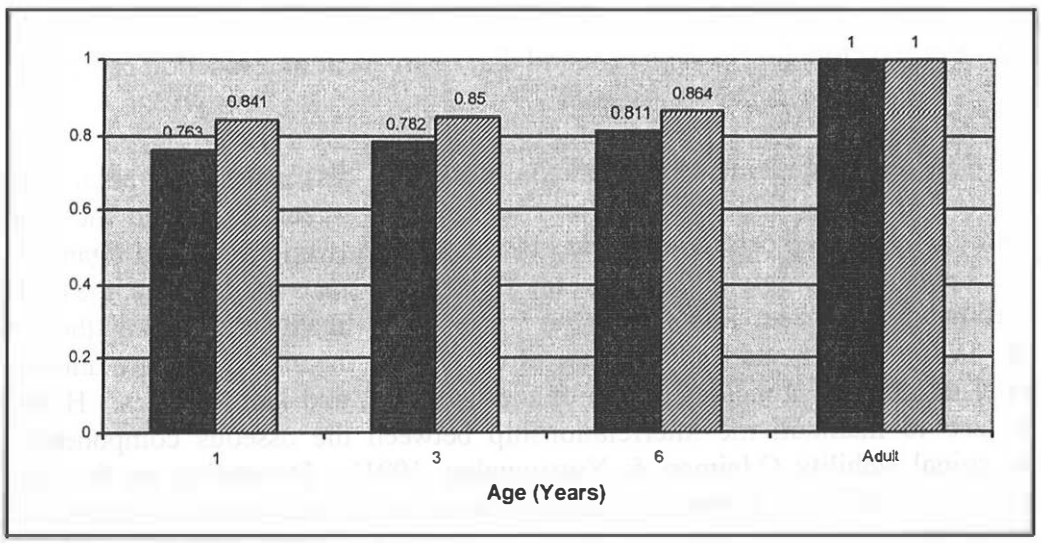

Fig. 1 - Scale factors for the cartilage component in compression (solid) and tension (lined) as a function of age.

Intervertebral Disc: The human intervertebral disc that exists caudally from the axis (C2) is a major load-carrying and transmitting component. The annular fibers of the disc mature in terms of density and structural stiffness. In contrast, the nucleus pulposus is incompressible and gelatinous (Ghosh, 1988). From a mechanical standpoint, the fibers of the annulus react to the external load including compression by hoop tension. The internal forces from the nucleus pulposus also contribute to the tensile stretch of the fibers (Yoganandan et al., 1987). Using published studies, a relationship was derived between age and failure tensile deformation of the disc (Galante, 1967). Scaling factors for the one, three

and six year old, expressed as a percentage of the adult, are shown in figure 2. The following equation was derived.

$$Y=1.657-0.021*A \quad (3)$$

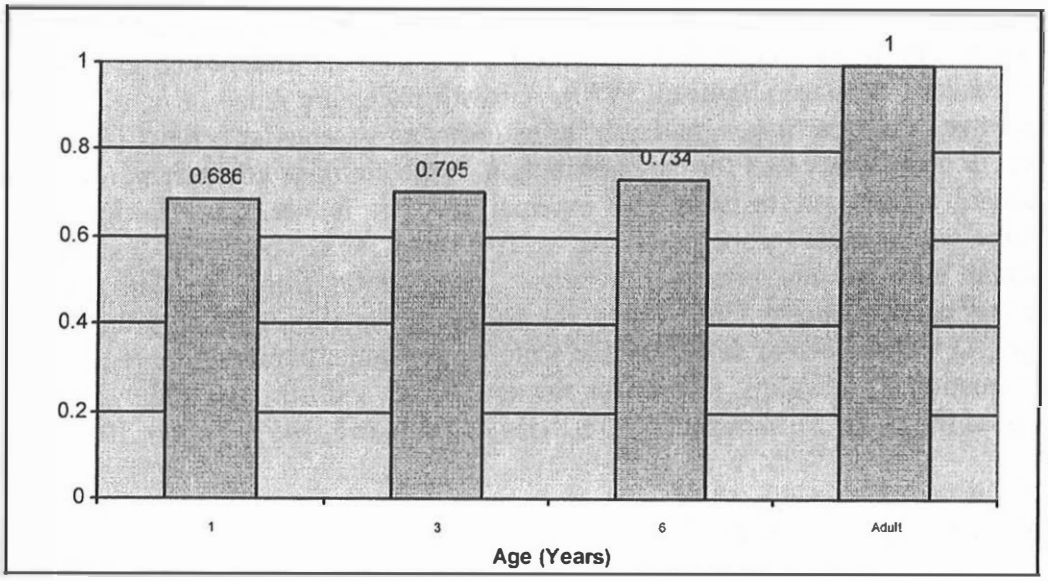

Fig. 2 - Scale factors for the intervertebral disc component as a function of age.

Spinal Ligaments: Ligaments are uniaxial structures that react to external load by tensile forces (Myklebust et al., 1988). The five major ligaments that span the cervical vertebrae from the axis to the cervico-thoracic junction are the two longitudinal ligaments on the anterior and posterior borders of the body, the flavum that spans the laminae, the capsular ligament surrounding the facet joints, and the interspinous ligament spanning the spines (Chazal et al., 1985). Ligaments from the base of the skull to the axis region are unique due to the occipital attachment processes, shape of the vertebrae, and lack of discs. However, their role is also to maintain the interrelationship between the osseous components and contribute to spinal stability (Maiman & Yoganandan, 1991). Depending on the type of external load vector, different ligaments actively contribute to the intrinsic biomechanical behavior. From an anatomical viewpoint, it is reasonable to consider the ligament in two groups: ligaments in the anterior and posterior regions. According to the two-column spine concept, longitudinal ligaments of the bodies are chiefly responsible for maintaining spine stability in the anterior column (Holdsworth, 1963; Yoganandan et al., 1999). Thus, this classification has a biomechanical basis. Using data from literature, the following equation (4) relating the deformation to age was derived to determine the scale factors for the longitudinal ligaments (Tkaczuk, 1968). For the ligamentum flavum, the following equation (5) relating stress to age was derived (Nachemson & Evans, 1968). The scale factors for the one, three and six year old, expressed as percentage of the adult, are shown in figure 3.

$$Y=0.73-72E-4*A+7E-5*A^2 \quad (4)$$
$$Y=121.2-1.53*A \quad (5)$$

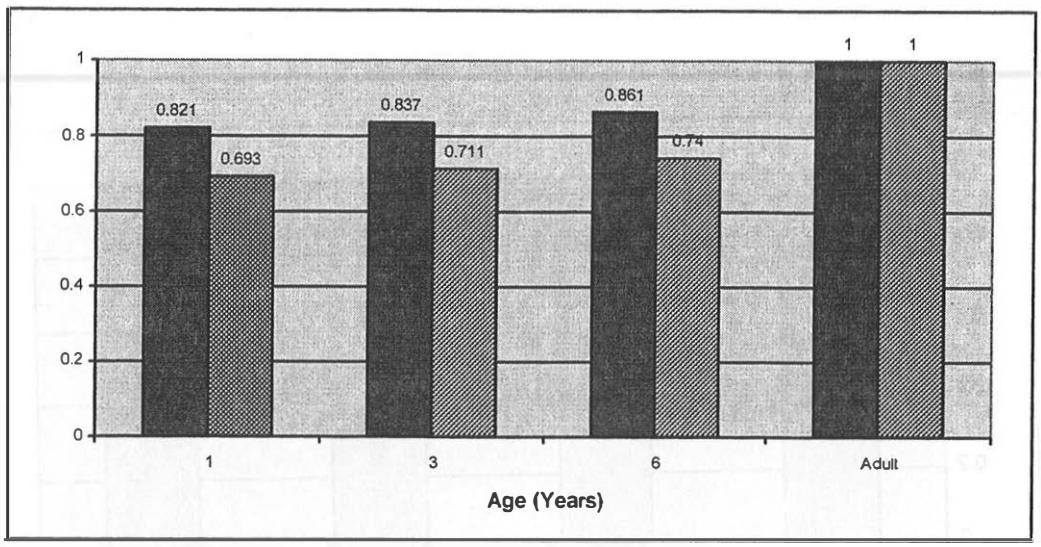

Fig. 3 - Scale factors for the longitudinal ligaments (solid) and ligamentum flavum (lined) as a function of age.

Since experimental data for the other ligaments in the posterior column are not available, and because of the similarities in the collagen fiber composition between the longitudinal ligaments and the ligaments of the posterior complex, i.e., interspinous and capsular ligaments, longitudinal ligament relationships can be used, as a first step, to include the dorsal ligaments. A similar analogy, when extended to the upper cervical anatomy, permits the use of these relationships for the suboccipital region. The ligamentum flavum is treated separately because of its unique characteristics in terms of a higher ratio of elastin to collagen compared to the other ligaments in the spinal column (Myklebust et al., 1988).

Vertebrae: Pediatric human cervical vertebrae, as indicated earlier, constantly develop after birth until skeletal maturity (Yoganandan et al., 2000). The process of primary ossification contributes to the maturation of neural canal anthropometry, fusion of the cartilage, and, to a certain extent, the onset of cervical lordosis (Bailey, 1952). In contrast, the secondary ossification process results in the maturation of endplates and formation of the uncovertebral anatomy including Luschka's joints, a characteristic feature in the development of the human cervical spine (Hall, 1965; Hayashi & Yabuki, 1985). In contrast to the adult spinal column, the vertebral cortex is not as developed and absent in the early stages of human growth. Consequently, as a first approximation, it is reasonable to use the cancellous bone as a structural component that deforms and responds to extend loading in order to determine the scale factor as a function of age. Using density data from literature, the following relationship (equation 6) was derived with respect to age (Gilsanz et al., 1988). Scale factors for the one, three and six year old groups, expressed as a percentage of the adult, are shown in figure 4.

$$Y=149.6+2.49*A \quad (6)$$

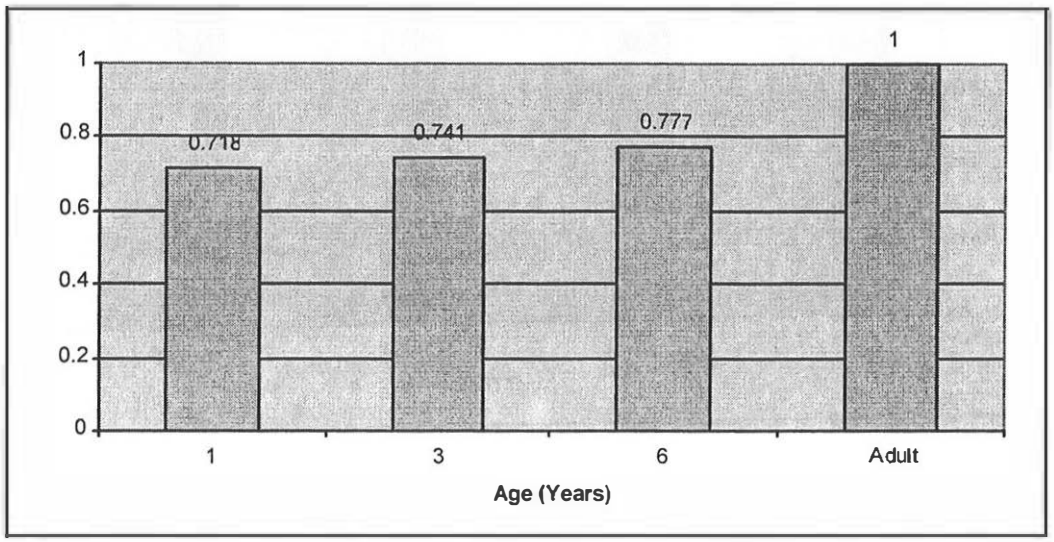

Fig. 4 - Scale factors for vertebrae as a function of age.

Spinal Cord: This neural structure is bound anteriorly by the body, and posteriorly and laterally by the neural arches of the vertebrae. The spinal cord stretches or shortens depending on the external load vector. Under a flexion bending moment, the canal elongates with the dorsal length exceeding the ventral length and under an extension bending moment, the reverse phenomenon is true. In lateral flexion, the contour of the canal differs by approximately 20 mm between the two opposing convex and concave curvatures (Breig, 1960; Scher, 1976). To determine scale factors, because of a lack of comprehensive data on the behavior of this tissue, as a first approximation, based on the above-cited studies, the following relationship was derived to represent the change in length as a function of age (equation 7). Scale factors for the one, three and six year old, expressed as a percentage of adult, are shown in figure 5.

$$Y=5.08-0.28*A+6E-3*A^2 \quad (7)$$

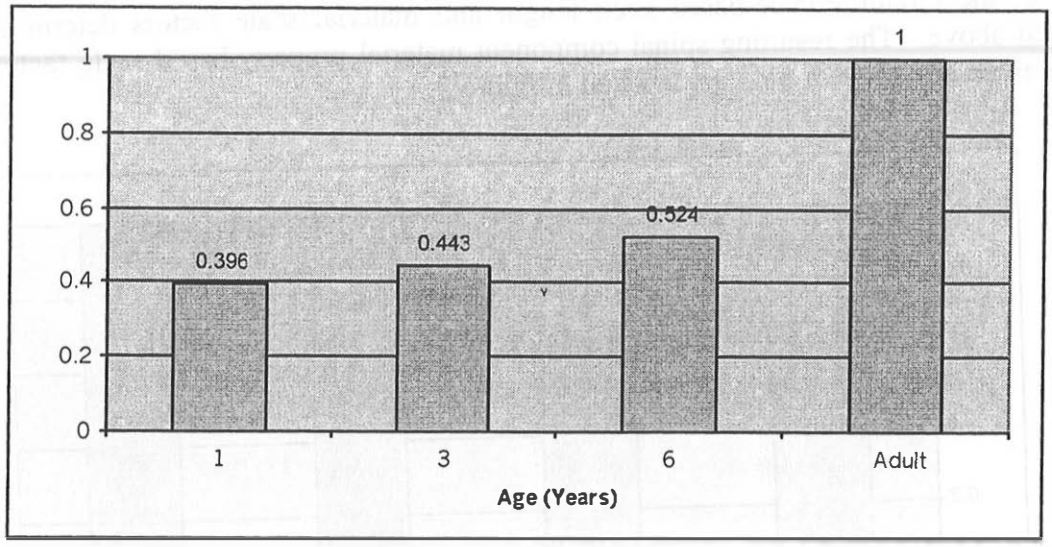

Fig. 5 - Scale factors for spinal cord as a function of age.

Muscles: It is well known that various muscles span the neck. While certain muscles are active in extension (e.g., trapezius), others respond under flexion (e.g., sternocleidomastoid). On a similar note, while certain muscles are very short and span only two vertebral levels (e.g., rotators), others span multiple levels or even from the base of the skull to the thoracic spine (Sherk et al., 1989). Furthermore, their line of action is dependent on factors including spinal curvature. A detailed study on the human neck muscle mechanics with regard to issues such as the load-carrying capacity is not available. Therefore, it may be reasonable to use the strength properties of the rectus abdominus skeletal muscle and derive the following equation (8) relating strength as a function of age (Katake, 1961). Figure 6 illustrates the scale factors for the one, three and six year old, expressed as a percentage of adult.

$$Y=24.52-0.45*A+3E-3*A^2 \qquad (8)$$

Geometry: Since the various constituents of the neck structures develop as a function of age, it is reasonable to incorporate these variations in order to derive scale factors. Neck length scale factors were determined using neck circumference data from anthropometric studies conducted in literature on adults and children of varying ages (Schneider, 1983; Snyder, 1977; Weber & Lehman, 1985). Figure 7 includes the scale factors as a function of age.

Scale Factors Under Tension: In order to determine the scale factors under tension, active components that resist the external distraction force were included. Because of the younger age group, the cartilage component was incorporated in the analysis. The active components were, therefore, the cartilage, vertebrae, intervertebral disc, ligaments (anterior atlanto-occipital membrane, tectorial membrane, longitudinal ligaments, interspinous ligaments, capsular ligaments, ligamentum flavum), spinal cord, and muscles. Using the relationships established for these components (Figures 1-6), a mean material scale factor that represents these elements is obtained as a function of age. To include neck geometrical changes due to age, circumference-based scale factor data (Figure 7) were used. Scale factors

for the force were obtained using the principles of dimensional analysis as the product of the square of the circumference-based neck length and material scale factors determined as described above. The resulting spinal component material property-based scale factors for the one, three and six year old, are depicted in figure 8.

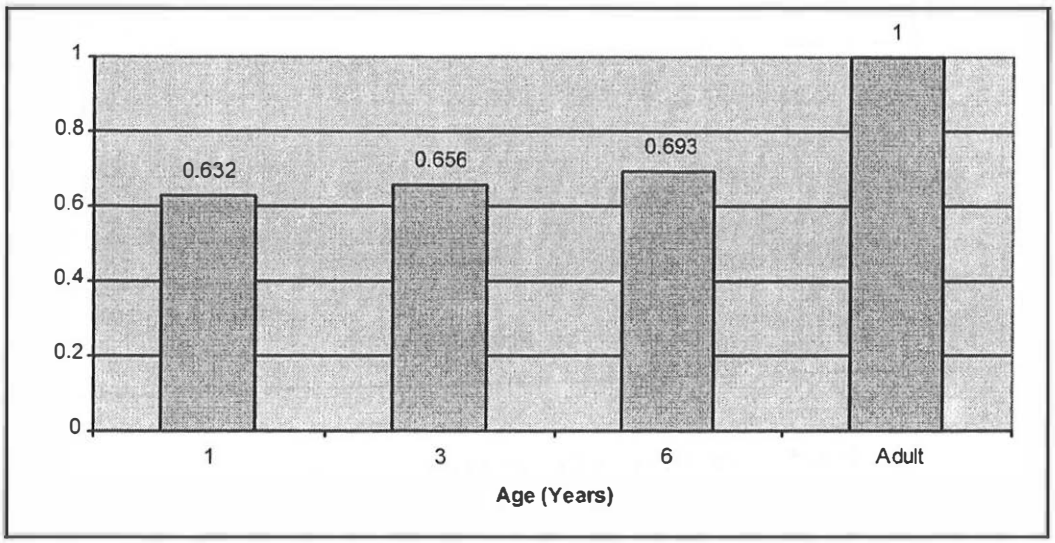

Fig. 6 - Scale factors for muscle as a function of age.

Scale Factors Under Tension: In order to determine the scale factors under tension, active components that resist the external distraction force were included. Because of the younger age group, the cartilage component was incorporated in the analysis. The active components were, therefore, the cartilage, vertebrae, intervertebral disc, ligaments (anterior atlanto-occipital membrane, tectorial membrane, longitudinal ligaments, interspinous ligaments, capsular ligaments, ligamentum flavum), spinal cord, and muscles. Using the relationships established for these components (Figures 1-6), a mean material scale factor that represents these elements is obtained as a function of age. To include neck geometrical changes due to age, circumference-based scale factor data (Figure 7) were used. Scale factors for the force were obtained using the principles of dimensional analysis as the product of the square of the circumference-based neck length and material scale factors determined as described above. The resulting spinal component material property-based scale factors for the one, three and six year old, are depicted in figure 8.

Scale Factors Under Extension Moment: The active elements of the human neck that resist extension bending moment are the cartilage, vertebrae, ligaments of the anterior column, spinal cord, and anterior and lateral neck muscles. Using the relationships established for these components (Figures 1-6), a mean material scale factor that represents these spinal elements was obtained as a function of age. Scale factors for the extension bending moment were obtained using the principles of dimensional analysis as the product of the cube of the circumference-based neck length scale factor and material scale factor determined as described above. The resulting spinal component material property-based scale factors for the one, three and six year old, are depicted in Figure 9.

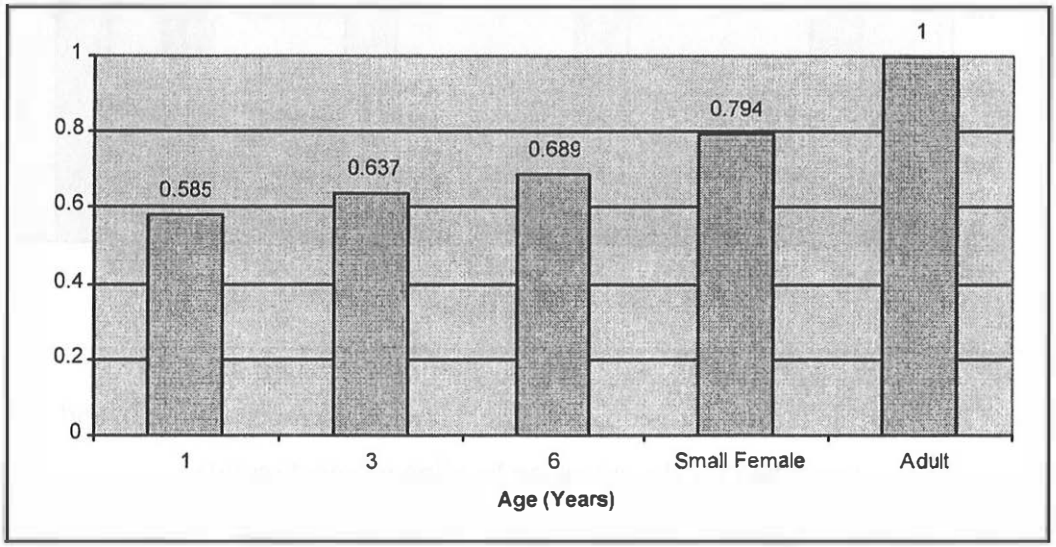

Fig. 7 - Scale factors for neck length based on circumference data as a function of age. The small female value is included for comparison.

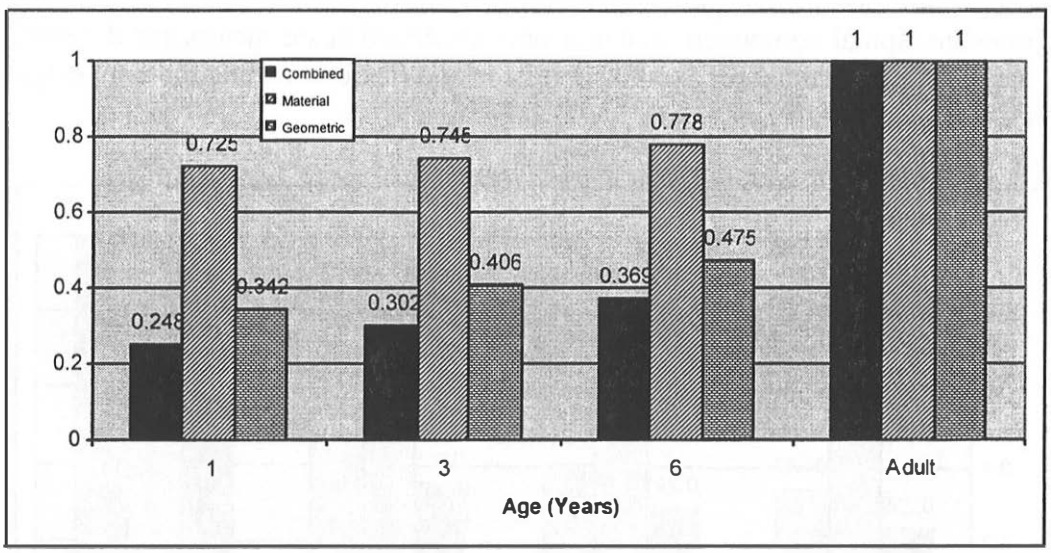

Fig. 8 - Scale factors for geometry (brick), material property (lined), and combined for the tension force (solid).

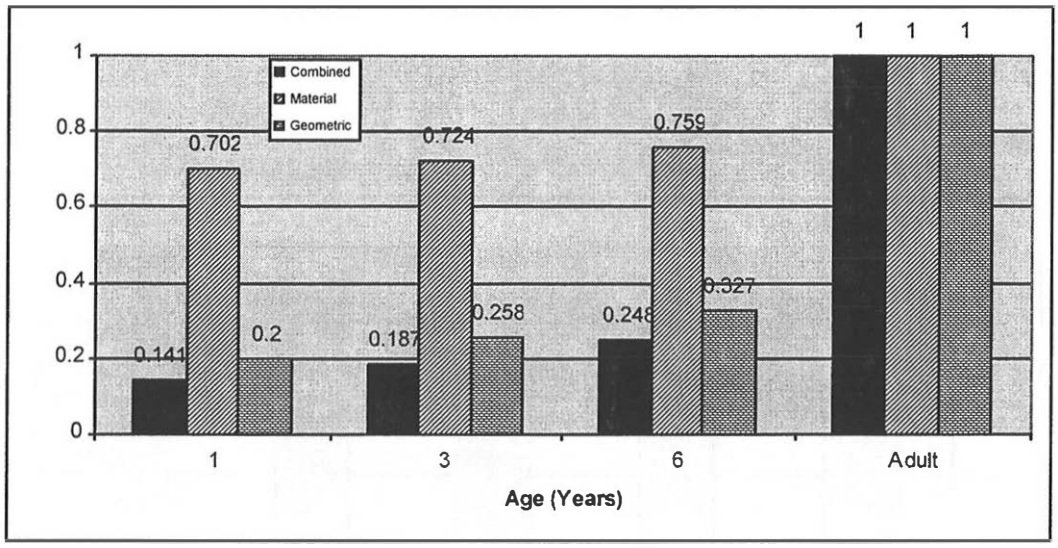

Fig. 9 - Scale factors for geometry (brick), material property (lined), and combined for the extension bending moment (solid).

Scale Factors for Compression and Flexion Bending Moment: Unlike the axial tensile force, the active components under compression are the cartilage, vertebrae, and intervertebral disc. Similarly, the active components under flexion bending moment are the cartilage, vertebrae, intervertebral disc, ligaments of the posterior complex, spinal cord, and flexor musculature. Using the principles described above for axial tension and extension bending moment, spinal component material property-based scale factors for the one, three and six year old were obtained for axial compression and flexion bending moment (Figures 10 and 11).

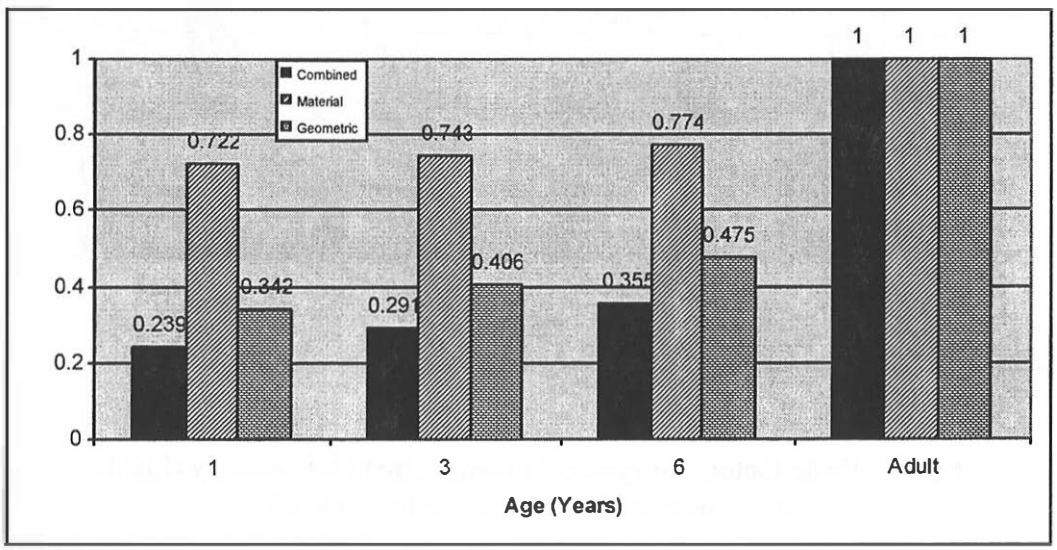

Fig. 10 - Scale factors for geometry (brick), material property (lined), and combined for the compression force (solid).

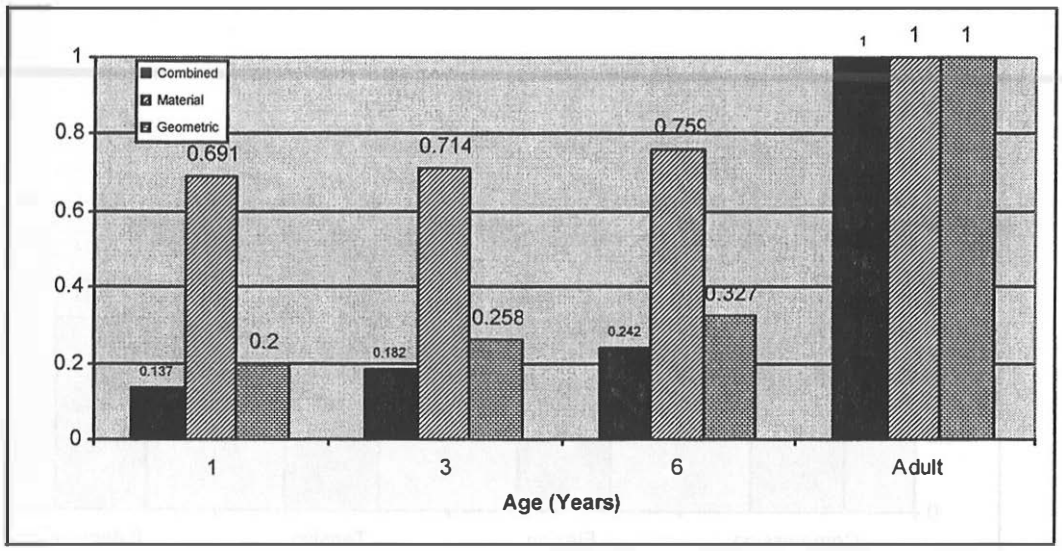

Fig. 11 - Scale factors for geometry (brick), material property (lined), and combined for the flexion bending moment (solid).

Scale Factors for the Small Female: The small female (5th percentile) has a lesser weight (49 kg) compared to the standard (50th percentile) male (78 kg). Neck geometrical differences between the two genders have been well established in terms of parameters such as neck circumference and length (1983). In contrast, material property data for the various spinal components as a function of gender are not currently available. Consequently, as a first approximation, it is reasonable to assume that there are no material differences between the two genders for the adult population. It should be emphasized that this assumption may not be completely valid for all ages since factors such as osteopenia or osteoporosis change the load-carrying capability of the vertebrae particularly for the female population (Pintar et al., 1998). On a similar note, early onset of spondylosis which is more frequent in men, may contribute to an altered load-sharing mechanism in the spinal column (Benzel, 1995). Using the above assumption, the following relationship was obtained for the small female scale factor for the two axial forces (compression, extension), and bending moments (flexion, extension). These are included in Figure 12.

Using the proposed critical values (N_{ij} criteria) for tension, extension, compression, and flexion, tolerances for different age groups based on spine component-derived scale factors were obtained. Briefly, the tension force and extension bending moment data for the three year old was obtained using experimental studies conducted on piglets and dummies (Mertz et al., 1982; Prasad & Daniel, 1984). Detailed statistical analyses were conducted on these data to establish tension and extension tolerances of 2120 N and 26.8 Nm (Eppinger et al., 1999). The reader is referred to these literature for additional details. Using the spinal component-based scale factors determined above (Table 1), tolerance values for the pediatric population were obtained. A comparison of these data with the tolerances determined from the scale factors based on calcaneal tendon strength data are included in table 2.

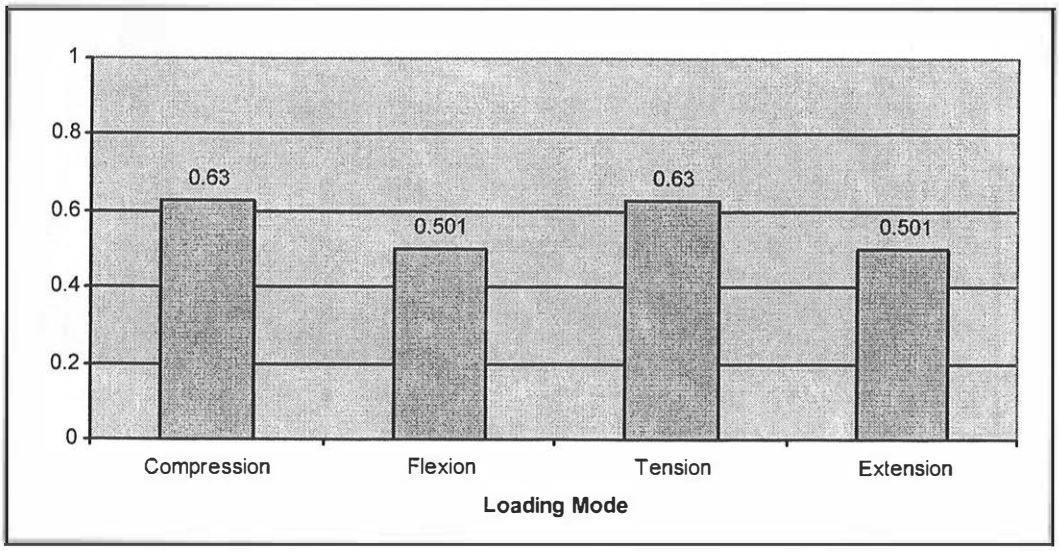

Fig. 12 - Scale factors for the small female (5th percentile) under compression, tension, flexion, and extension based on pure geometrical scaling.

Table 1: Comparison of Scale Factors

Age (Years)	Based on Calcaneal Tendon Material Property*		Based on Spinal Component Material Property			
	Tension	Extension	Tension	Extension	Comp.	Flexion
1	0.24	0.14	0.248	0.141	0.239	0.137
3	0.34	0.22	0.302	0.187	0.291	0.182
6	0.46	0.31	0.369	0.248	0.355	0.242
5th female	0.63	0.50	0.630	0.501	0.630	0.501
50th male	1.00	1.00	1.000	1.000	1.000	1.000

*: Scale factors for compression = tension and flexion = extension, and scale factors for 5th female are based on pure geometrical scaling only (Figure 12).

DISCUSSION

A method was developed in this study to derive neck scale factors for the pediatric population based on material property information extracted from studies conducted using human spine structures. Because data were incorporated from individual spinal components, it was possible to derive scale factors under all four loading modes, i.e., tension, extension, compression and flexion, by identifying the appropriate active components under each mode. This is in contrast to the previously reported scale factor method which was based on tensile strength data extracted from a single structure, i.e., the human calcaneal tendon. However, it should be noted that all data were based quasi-static testing results; dynamic scale factors may differ. This is true for the scale factors based on the calcaneal tendon. The spinal cord and dura offer resistance similar to the interspinous ligaments and therefore the cord was included in the computation of scale factors. Thus, all relevant structural components were considered in this study.

Table 2: Critical Tolerance Values for N_{ij} Criteria

Age (Years)	Based on Calcaneal Tendon Material Property				Based on Spinal Component Material Property			
	Tension (N)	Ext. (Nm)	Comp. (N)	Flexion (Nm)	Tension (N)	Ext. (Nm)	Comp. (N)	Flexion (Nm)
1	1460	17	1460	43	1740	20	1740	50
3	2120	27	2120	68	2120	27	2120	68
6	2800	37	2800	93	2590	36	2585	89
5th female	*3880	61	*3880	155	*4420	72	*4435	182
50th male	*6160	125	*6160	310	*7015	143	*7030	363

*: Experimental data for axial load limits for adult dummies are lower.

Using the tendon data, scale factors can only be derived for tension and extension loading modes. The determination of loading mode-dependent scale factors for all four modes using the spinal component material property information is a merit of the present study. Furthermore, since material scale factors for neck tolerance are based on the material properties of the interconnecting spinal tissues, the present method, in principle, is superior to the tendon scaling method. In a sense, the currently derived scale factors provide an overall first level of validity to the tendon scaling method, although differences exist between the two sets of numerics. It should, however, be emphasized that the present analysis is based on information from a variety of experimental sources. Consequently, non-uniform variations imminent in the experimental designs and their outcomes were not accounted for in this study. With regard to the small female population, scale factors accounted for the geometric differences between this and the mid-size male with no consideration to the differences that may exist in the material properties between the two groups. This is due to the lack of gender-based material property data that exist in literature. However, when such data are available, it will be possible to refine the present approach to more accurately estimate the scale factors for all populations.

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