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Characterization of the age-dependent shape of the pediatric thoracic spine and vertebrae using generalized procrustes analysis

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ABSTRACT

Generalized Procrustes Analysis (GPA) is a superimposition method used to generate size-invariant distributions of homologous landmark points. Several studies have used GPA to assess the three-dimensional (3D) shapes of or to evaluate sex-related differences in the human brain, skull, rib cage, pelvis and lower limbs. Previous studies of the pediatric thoracic vertebrae suggest that they may undergo changes in shape as a result of normative growth. This study uses GPA and second order polynomial equations to model growth and age- and sex-related changes in shape of the pediatric thoracic spine. We present a thorough analysis of the normative 3D shape, size, and orientation of the pediatric thoracic spine and vertebrae as well as equations which can be used to generate models of the thoracic spine and vertebrae for any age between 1 and 19 years. Such models could be used to create more accurate 3D reconstructions of the thoracic spine, generate improved age-specific geometries for finite element models (FEMs) and used to assist clinicians with patient-specific planning and surgical interventions for spine deformity.

1. Introduction

Generalized Procrustes Analysis (GPA) is a superimposition method introduced by Gower (1975) and popularized by Rohlf and Slice (1990) which can be used to generate size-invariant distributions of homologous landmark points (LMPs) identified on a series of target objects by minimizing the Euclidean distances between corresponding LMP sets (Gower, 1975; Rohlf and Slice, 1990). Several studies have used GPA to assess three-dimensional (3D) shapes or to evaluate sex-related differences in the human brain, skull, rib cage, pelvis and lower limbs (Bastir et al., 2013; Betti, von Cramon-Taubadel, Manica, & Lycett, 2014; Bompard et al., 2014; Domjanic, Seidler, & Mitteroecker, 2015; Wang et al., 2016; Weaver et al., 2014b). However; to the authors' knowledge no attempts have been made to quantify the 3D shapes of the pediatric thoracic spine or vertebrae.

Previous studies of pediatric thoracic vertebral growth have found that while the size of the spinal canal remains relatively constant from early life into maturity, dimensions of the vertebral bodies, facets, pedicles, and processes continue to increase with age (Ferree, 1992; Lord et al., 1995; Peters et al., 2015; Taylor, 1975; Veldhuizen et al., 1986; Zhang, Sucato, Nurenberg, & McClung, 2010; Zindrick et al., 2000). This suggests that the vertebrae may be undergoing changes in shape. 'Shape', in this context, refers to the relative size, position, and orientation of the different vertebral structures when the overall scale of the vertebra is held constant. While the aforementioned studies can provide the age-, sex- and level-specific magnitudes of the pediatric thoracic vertebral structures, no data describing their global anatomical position, orientation or shape were reported. Such information derived from the normative pediatric population could be combined with stereophotogrammetric reconstruction to create more accurate age-specific geometries for finite element models (FEMs) and used to assist clinicians with patient-specific planning and surgical interventions for spine deformity.

Volumetric FEMs of the thoracic spine are typically created using surface geometries obtained from manually segmented CT scans or stereo X-ray reconstruction of the vertebrae (Driscoll, Mac-Thiong, Labelle, & Parent, 2013; Little & Adam, 2011; Nie, Ye, Liu, & Wang, 2009; Villemure, Aubin, Dansereau, & Labelle, 2004; Wang et al., 2014). While stereo reconstruction is a fast alternative to CT reconstruction, the technique requires pre-made, template surface models of the vertebrae which can be registered to a set of LMPs identified on both the radiographs

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and the surface models (Mitton et al., 2000; Pomero et al., 2004). Age-dependent LMP data from the pediatric population could be freely combined with these template models to create more accurate representations of the vertebral surfaces resulting in improved reconstructions and FE simulations (Meijer et al., 2010; Niemeyer et al., 2012). Similarly, these data could be used to create graphical models which would aid clinicians in the planning of growth-friendly treatments for spine deformity. Spinal growth modulation is becoming an increasingly popular area of research which promises to restore the normative morphology of the spine while preserving its range of motion (Jain et al., 2014; Skaggs et al., 2014). Fundamentally, growth modulation relies on an understanding of normative spine geometry and its development. Using normative, age-dependent LMP data from the thoracic spine and 3D reconstructions of a spine deformity, one could directly observe the differences in size, orientation, and shape between normal and deformed conditions at a specific age, allowing clinicians to make more informed decisions regarding treatment.

Hence, the objectives of the current study were to (1) generate GPA-based models of the 3D shapes of each pediatric thoracic vertebra (T1-T12), (2) characterize the shape, global position, and orientation of the individual vertebrae and whole thoracic spine as a function of age, and (3) evaluate sex-related differences in the resulting age-dependent descriptions.

2. Methods

2.1. Subject sample

Retrospectively obtained, chest, computed tomography (CT) scans from 91 skeletally normal subjects (38 males, average age: 9.29 ± 5.83 years, range: 1.1–18.42 years, average body mass index (BMI): 18.81 ± 3.78 kg/m^2, range: 15.45–36.34 kg/m^2 and 53 females, average age: 9.69 ± 5.92 years, range: 1.18–18.78 years, average BMI: 18.98 ± 3.42 kg/m^2, range: 14.42–26.95 kg/m^2) were obtained from the Department of Radiology at the Children's Hospital of Philadelphia (CHOP). All subjects were chosen to be within 5th and 95th percentiles in height, weight and BMI, as determined by CDC growth charts for children and by CDC NHANES data for subjects 18 years and older ("CDC - National Center for Health Statistics - Growth Charts,"; Frayer et al., 2012). CT scans with axial slice thickness of up to 5 mm with an in-plane resolution of 0.658 by 0.658 mm were considered for analysis. Subject CTs were digitally reconstructed using the medical image processing software MIMICS (Materialise Inc., Belgium) using a preset threshold for bone, and the thoracic vertebrae (T1-T12) were manually segmented. The resulting models were further refined using 3-matic (Materialise Inc., Belgium), filling holes and increasing surface mesh density as needed.

2.2. Landmark point collection and coordinate systems

To aid in the identification of homologous LMPs each 3D vertebra model was first aligned with a prepositioned thoracic level-specific surface template using an iterative closest point (ICP) algorithm (Besl and McKay, 1992). This prepositioning allowed for the identification of concurrent cross-sectional outlines, using an alpha shape algorithm, which were further assessed to robustly identify the region-specific extrema that define the various vertebral structures (Edelsbrunner et al., 1983). Through these methods, thirty surface landmark points (LMPs) were automatically identified using a custom MATLAB (The MathWorks Inc, Natick, MA) script. The LMPs collected during this study were comparable to those previously reported in the literature for geometric quantification, statistical modeling, and 3D reconstruction of the spine (Balasubramanian et al., 2016; Delorme et al., 2003; Le Bras et al., 2003; Mitulescu et al., 2001; Peters et al., 2015; Pomero et al., 2004). Fourteen LMPs were selected on the sagittal and coronal cross-sections of the vertebral body, four were identified on each pedicle with an additional LMP on the posterior wall of the spinal canal, two LMPs were located at the lateral tips of the transverse processes, one was found at the apex of each superior and inferior articular process (facet), and one LMP specified the inferior tip of the spinous process (Table 1, Fig. 1). Due to the inherent variation of the facet structures, the LMPs denoting the apices of the facets could not always be identified automatically and were manually adjusted when needed. To validate the quality of this landmark point identification method, a repeatability study was performed. The interclass correlation (ICC) across all thoracic vertebral levels was 0.9989 for landmark points collected by a single observer from reconstructions of the same subject at two different time points, months apart.

To maintain a consistent orientation for the thoracic vertebrae across subjects, each thoracic spine LMP set was translated such that its centroid aligned with the global origin. Here, the centroid was the unweighted average of the X, Y and Z spatial data

Table 1
Landmark point numeration and identification.

Vertebra structure	Landmark point	Description of landmark point location
Vertebral body	LMP1	Center of superior endplate
	LMP2	Anterior most superior point of the midsagittal cross section
	LMP3	Anterior most mid-point of the midsagittal cross section
	LMP4	Anterior most interior point of the midsagittal cross section
	LMP5	Center of inferior endplate
	LMP6	Posterior most inferior point of the midsagittal cross section
	LMP7	Posterior most mid-point of the midsagittal cross section
	LMP8	Posterior most superior point of the midsagittal cross section
	LMP9	Right most superior point of the mid-vertebral body coronal cross section
	LMP10	Right most mid-point of the mid-vertebral body coronal cross section
	LMP11	Right most inferior point of the mid-vertebral body coronal cross section
	LMP12	Left most superior point of the mid-vertebral body coronal cross section
	LMP13	Left most mid-point of the mid-vertebral body coronal cross section
	LMP14	Left most inferior point of the midsagittal vertebral body cross section
Pedicles	LMP15	Superior midpoint of the left pedicle
	LMP16	Medial midpoint of the left pedicle
	LMP17	Inferior midpoint of the left pedicle
	LMP18	Lateral midpoint of the left pedicle
	LMP19	Superior midpoint of the right pedicle
	LMP20	Medial midpoint of the right pedicle
	LMP21	Inferior midpoint of the right pedicle
	LMP22	Lateral midpoint of the right pedicle
Spinal canal	LMP23	Posterior wall of the spinal canal
Facets	LMP24	Apex of the right superior facet
	LMP25	Apex of the right inferior facet
	LMP26	Apex of the left superior facet
	LMP27	Apex of the left superior facet
Transverse processes	LMP28	Apex of the right transverse process
	LMP29	Apex of the left transverse process
Spinous process	LMP30	Most inferior and posterior point