1. Introduction

Craniovertebral (CV) spinal instability continues to be a major concern due to the importance of the CV junction in maintaining neurological and physiological viability. Located at the upper cervical spine region, the CV junction serves as a base for optimal head movement while simultaneously protecting surrounding neurological components during cranial movement. If destabilized, excessive motion of CV segments could significantly compromise neurological and physiological function. Individuals diagnosed with Klippel-Feil Syndrome (KFS) exemplify such destabilization (1,2). Although fusion and instability appear to be correlated, more intrinsic evaluation of KFS-related instabilities is needed. Current KFS studies have been unsuccessful in identifying factors that contribute to CV destabilization in the presence of congenital CV-C2 fusion. It has been hypothesized that vertebrae fusion induces abnormal stress distributions, catalyzing the development of fracture at the CV junction. The purpose of this presentation is to illustrate the use of Finite Element (FE) Modeling and Analysis in characterizing motion and irregular stress distributions of a pediatric upper cervical spine affected with KFS between CV-C2 (KFS). For comparison purposes, age- and sex-matched normal upper cervical FE model have also been developed (Norm).\n
2. Methods

2.A) Model Generation

Both FE models were built using Computer Tomography (CT) images, as shown in Fig. 1, from upper cervical spine scans of one normal and one KFS 11yo, male patient. The modeled cervical spine segments span from the Occiput through C5. CT images of the Normal spine model were scanned at 0.625 mm increments, with 0.310 mm image slice thickness while the K2-S model was scanned at 1.25 mm increments and slice thickness of 1.13 mm. Mimics Image Processing Software (Materialise, v11.11) was used for full-scale, geometric computational reconstruction of the spine segments. Model construction was performed in a smooth and assigned triangular volume elements using the 3D calculation functionality of Mimics. Solid body meshing was performed using a computer aided modeling software, PATRAN (MSC Software v2007.3), converting triangular surface mesh elements into 4-node linear tetrahedral volumetric (CT40) elements allowing for non-homogenous material assignment using Mimics.

2.B) Material Properties Assignment

CT Hourglass attenuation conversions were performed by Rho et al. (3) were used to assign nonhomogenous volumetric elements of cancellous and cortical bone regions with mass densities of 0.1-1.1 x 10³ kg/m³ and 1.1-1.8 x 10³ kg/m³, respectively (4). Next, material properties (identical for both models) were paired to corresponding densities of each Transversely isotropic volumetric elements to aid the assignment of Young’s (E) and Shear Modulus (G) and Poisson’s Ratio (ν) (Table 1). In contrast, articular cartilage (AC), between the occipito-atlanto and atlanto-axial joints and intervertebral discs (IVDs) were modeled as homogenous with a width of 25 mm and E = 10⁴ Mpa and G = 10⁴ MPa (5.6). Axial connection elements, active only in tension, were used to model the apical, left and right art, anterior and posterior longitudinal, transverse capsular, supraspinous, interspinous, and transverse atlanto-occipital ligaments present in both models assigned with identical material properties (7).\n
3. Results

3.A) Flexion (Anterior View)

As shown, the deflection resulted in induced strain of the K2-S model is less than that observed in the Normal model. This appears to be the direct result of reduced flexibility due to the absence of IVDs within the fusion region.

3.B) Extension (Anterior View)

The absence of IVDs within the K2-S model resulted in significant propagation of large magnitudes of stress through regions of fusion.

Under identical loading conditions and material properties, the KFS model clearly demonstrates the effects of abnormal vertebral geometry on intersegmental motion, resulting stress magnitudes, and stress propagation where the K2-S model expressed lower mobility and higher stress expressions.

4. Discussion

The goal of the computational simulation was to provide an intrinsic perspective of stress propagation within a fused vertebral segment in the presence of KFS. During the application of the three static loading conditions, flexion resulted in the largest reactionary stresses in the segment, followed by lateral bending then extension. In addition, rightward lateral bending was accompanied by an unforeseen leftward axial twist. This can be a direct compensatory response of the K2-S segment to the inherent altered vertebral anatomy. It is also important to note that the resultant stresses of the K2-S model is much more expressive throughout the segment when compared to the Normal model. This may be the direct result of reduced mobility within in the absence of IVDs between C2 through C5 of the KFS model. The maximal magnitude of the K2-S stresses were also significantly higher than those of the Normal model in all conditions except in K2-S Extension. Also, the average stresses at the C2-3 motion segment were lower in the K2-S model mainly due to a lack of lever arm (missing discs) during loading (Table 2).

The ranges of motion between C2-3 in the K2-S model were also 50% lower in all three loading conditions (Table 3). The largest motion for both models was in flexion in contrast to the lowest motion induced under extension. For the K2-S model, the increased stiffness of the segment due to fusion meant the largest contributor to flexion and extension was due to the innate articulation of the occipito-atlantal joint, resulting in the stress accumulation observed at the upper regions of the fused C2-S5 region that is absent in the Normal model during Flexion/Extension.

As a result, it can be concluded that changes in vertebral anatomy adversely affect inherent mobility and stress propagation of the segment, thereby contributing to the development of abnormal stress patterns that may lead to instability elsewhere within a fused segment. Specifically, the absence of IVDs in such a KFS model decreases flexibility and validates the introduction of extended lever arms on adjacent segments (10), causing unwarped stress patterns. The results validate the use of FE Modeling to further investigate the effects of fusion related stress distribution which could lead to greater understanding of fusion-related instabilities, particularly among KFS patients through virtual evaluation of biomechanical changes caused by vertebral fusion.

5. References