Introduction:

Klippel Feil Syndrome (KFS) is a congenital disorder characterized by failure of segmentation of cervical vertebrae, resulting in “fusions” at any level of the cervical spine. Clinical diagnosis of KFS occurs at a mean age of 7.1 years. Children diagnosed with KFS often exhibit reduced motion and function characterized by reduction of upward and downward deflections of the head on the neck (flexion/extension), horizontal twisting (axial rotation), and tilting of the head (lateral bending). More importantly, however, previous KFS studies have acknowledged possible complications to the structural integrity and overall health of the cervical spine in the presence of abnormal fusion. Instances of instabilities such as fracture and hypermobility at vertebral segments adjacent to fusion have been recorded, both posing significant neurological and physiological dangers to an individual afflicted with KFS.

While fusion and instability appear to be interrelated, more intrinsic evaluations of KFS-related instabilities are needed. Currents KFS studies, relying predominantly on static radiographic modalities, have been unsuccessful in identifying factors contributing to cranio-cervical (CC) destabilization in the presence of congenital vertebral fusion. It has been hypothesized that the most prevalent KFS related C2-C3 vertebral fusion induces abnormal stress distributions, which catalyze the fracture developments at the base of the second cervical vertebra.

The purpose of this research is to utilize Finite Element (FE) Modeling and Analysis to characterize motion alterations and irregular stress patterns of a KFS afflicted upper cervical spine. The results of the high-fidelity computational simulation will be compared to a similar model of a normal age and sex matched cervical spine to elucidate biomechanical variations associated with abnormal vertebral segmentation. More importantly, the research hopes to validate the use of FE modeling and initiate the use of high fidelity computational modeling as an additional, clinically viable diagnostic modality.

Methods:

A three-dimensional upper cervical spine FE model was developed from Computer Tomography (CT) data of a pediatric patient clinically diagnosed with KFS. The modeled cervical spine segment extends from the C2 vertebra to C5. CT images of the spine segment were scanned at 0.625 mm increments, with 0.310 mm image slice thickness and a resolution of 512x512 pixels. Full-scale, geometric computational reconstruction of the affected spine segment was achieved using Mimics Image Processing Software (Materialise, v.11.11). Vertebrae C2 thru C5 were modeled as one continuous unit due to severity of fusion. Intervertebral discs (IVDs) were not modeled in the target spine region.

Vertebral components were smoothed and assigned triangular volume elements using the 3D calculation functionality of Mimics. Solid body meshing was performed using PATRAN (MSC Software v.2007 R1B) to convert triangular surface mesh elements into 4-node linear tetrahedral volumetric elements to allow for material properties identification using Mimics. A set of formulations created by Rho et al correlating CT Hounsfield attenuation characteristics and bone densities was used to non-homogenously distribute and assign cortical and cancellous bone regions to each volumetric element of the model. The modeled segment was then exported into the finite element analysis module ABAQUS (Simulia, v6.8-3) for material properties assignment and appropriate Finite Element Analysis.

Baseline bone density values of 1.8 x 10^6 kg/m^3 and 0.9-1.1 x 10^6 kg/m^3 were used to identify cortical and cancellous bone regions of each rendered volumetric element. Each volumetric element was classified as Transversely Isotropic, with corresponding assignment of Young’s Moduli, Shear Moduli, and Poisson’s Ratio. Boundary conditions constraining translational and rotational motion were applied to the undersurface of the modeled C5 vertebra during analysis. A 50 Newton (N) uniaxial load representing the weight of the cranium was uniformly distributed among the superior condyles of C2. Flexion/extension, lateral bending, and axial rotation, were all induced with 1.5 Newton-meter (Nm) moments. Model stresses were computed through visual representations and numerical assignment of Von Mises Stress values. The resulting model contains 102059 active tetrahedral elements and 18491 nodes.

Table 1: Range of Motion Values

<table>
<thead>
<tr>
<th>Method</th>
<th>Flexion/Extension</th>
<th>Lateral Bending</th>
<th>Axial Rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cadaveric</td>
<td>6.2°</td>
<td>9.6°</td>
<td>3.3°</td>
</tr>
<tr>
<td>3D MRI</td>
<td>1.4°</td>
<td>3.6°</td>
<td>2.2°</td>
</tr>
<tr>
<td>F.E. Analysis</td>
<td>10.0°</td>
<td>4.8°</td>
<td>5.0°</td>
</tr>
</tbody>
</table>

Table 1 - Range of Motion Values: ranges of motion comparisons of current model cervical spine studies of normal intact segments, KFS reflected congenital fusion, and drastically reduced motion of the target segment, which moves as a singular unit.

Discussion:

The goal of the computational simulation was to provide an intrinsic viewpoint of stress propagation and motion alterations accompanying KFS. The model created demonstrates the drastic reduction in range of motion when cervical segments C2-C3 are fused. Even though the current model represents a more extensively fused segment spanning C2-C5, it does provide an insightful perspective on the abnormal stress distribution associated with KFS. Compared to normally segmented spines, the range of motion data of the current model is significantly less, especially in lateral bending (Table 1). Although flexion/extension resulted in the largest overall motion, intervertebral motion was essentially non-existent as the modeled segment responded as a singular unit. Lateral bending resulted in minimal motion although the resulting stress magnitudes lay between those induced by flexion/extension and axial rotation.

Furthermore, stresses induced from the three loading conditions also propagated through the entirety of the vertebral segment. Axial rotation induced the largest reactionary stresses from the segment, followed by lateral bending and flexion/extension. This transmission of stress within the segment can be hypothesized to result from the lack of mobility within the segment due to the absence of IVDs between cervical segments C2 through C5 in the current model. It was also observed that an increase in loading moment magnitude resulted in an increase in stress. In this regard, abnormal fusion is demonstrated to adversely affect adjacent vertebral segments. To further confirm the susceptibility of fracture induced by KFS, additional simulations using larger loading magnitudes with auxiliary soft tissue include were analyzed.

From the results, 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 instability elsewhere within a fused segment. Although the current model has an incomplete cranio-cervical complex, it demonstrates that further investigation into the effects of fusion and stress distribution could lead to a greater understanding of fusion-related instabilities, particularly among KFS patients. The current model also presents the possibility of utilizing FE modeling as a diagnostic tool aiding in the evaluation of the biomechanical effects of vertebral fusion and validating treatment options in the presence of instability.