Introduction:

Klippel Feil Syndrome (KFS) refers to a congenital disorder characterized by abnormal segmentation of vertebral bodies, resulting in “fusions” that may manifest at level of the spine. Predominantly, however, fusions typically affect upper cervical spine segments. Clinical diagnosis of KFS usually occurs among children where patients affected by the condition exhibit reduced functionality and ranges of motions during flexion/extension (upward and downward deflections of the head on the neck), lateral bending (tilting of the head), and axial rotation (horizontal twisting). In addition, previous KFS studies have also acknowledged possible compromises 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 sites of fusion have also been noted to pose significant compromises to surrounding neurological and physiological of the cranoicervical junction.

Previously research utilizing Finite Element (FE) Modeling and Analysis of KFS by the current group yielded a more intrinsic evaluation of KFS-related instabilities, where fusion of the upper cervical spine resulted in excessive loss of motion and comparably higher Von Mises stresses. Building upon those results, the current research seeks to provide a more comprehensive validation of those findings by virtually disrupting the site of fusion and determine the associated alterations in biomechanics of the spine. Specifically, the results of the current simulations is to validate the possibility of utilizing computational simulations as a mean of “pre-planning” surgical interventions as well as provide a more in-depth validation of KFS biomechanics.

Methods:

Two upper cervical spine three-dimensional FE models spanning from the Occiput to the C6 vertebrae were developed from Computer Tomography (CT) data of two pediatric patients: one of normal upper cervical anatomy (11 year old male) and the other clinically diagnosed with KFS-related fusion at the C2-C3 motion segment (10 year old female). A third model simulating a virtual vertebrectomy was derived from the fused spine segment by replacing a portion of fusion with an artificial spacer assigned with properties of an intervertebral disc (IVD). Full-scale, geometric computational reconstruction of all spine segments was achieved using Mimics Image Processing Software (Materialise, v.11.11).

Osseous and intervertebral disc (IVD) components were then 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. The modeled segment was then exported into the finite element analysis module ABAQUSS (Simulia, v6.8-3) for material properties assignment and analysis.

Formulations created by Rho et al were used to correlate CT Hounsfield attenuation with bone densities to non-homogenously assign cortical and cancellous bone regions among the models. Regions with calculated densities between 0.1 - 1.09 x 10^6 kg/mm³ were assigned Cancellous bone properties while Cortical bone regions were marked within the density range of 1.1 - 1.8 x 10^6 kg/mm³. All models and their elements were classified to be Transversely Isotropic, with identical assignment of Young’s Moduli, Shear Moduli, and Poisson’s Ratio based on interpolation of existing literary values. IVDs were modeled as cylindrical solids and also assigned material property values based on existing literature.

Matching boundary conditions constraining unwarranted translational and rotational motion were to all modeled segments. Flexion/extension, lateral bending, and axial rotation, were all induced at 0.25 Newton-meters (Nm) increments to a maximum of 2.0 Newton-meters (Nm) via a load plate. Model stresses were then captured visually and numerically for comparative purposes.

Results:

Table 1 - Range of Motion Values: Comparisons of total segment motions among the three modeled cervical spines: Normal (Norm), KFS related C2-C3 fusion (K23), and the virtual vertebrectomy model (K23V). As shown, the largest restorations in motions were associated with Flexion-Extension and Lateral Bending.

<table>
<thead>
<tr>
<th>Model</th>
<th>Flexion/Extension</th>
<th>Lateral Bending</th>
<th>Axial Rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Norm</td>
<td>17.9°</td>
<td>30.7°</td>
<td>50.4°</td>
</tr>
<tr>
<td>K23</td>
<td>14.8°</td>
<td>9.5°</td>
<td>52.9°</td>
</tr>
<tr>
<td>K23V</td>
<td>21.1°</td>
<td>14.4°</td>
<td>55.1°</td>
</tr>
</tbody>
</table>

Discussion:

The purpose of the current computational simulation was to provide additional insight regarding the loss of motion and increase of stress response among KFS segments. Through the simulation of a virtual vertebrectomy, an extreme but plausible solution in alleviating the adverse effect of fusion on adjacent vertebral segments. More importantly, the results illustrate the possibility of utilizing computation methods in the validation and development of suitable methods of interventions. To further confirm the susceptibility of fracture induced by KFS, additional simulations using larger loading magnitudes with auxiliary soft tissue include will be performed.

Significance:

From the results, the reduction in stress and restoration of motion due to the simulated vertebrectomy validates the development of instability elsewhere within a fused spine segment. 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.