THE BIOLOGICAL IMPLICATIONS OF VARYING ELEMENT DESIGN IN FINITE-ELEMENT SCALING ANALYSES OF GROWTH

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ABSTRACT

Three-dimensional coordinates of osseous biological landmarks located on computed tomographic (CT) images provide a valid geometric model of a class of anatomical information present in a CT image. We have used sets of landmarks located on CT images to determine the changes in form that occur during growth of the head. Finite-element scaling analysis provides a quantitative and graphic mapping of a younger individual into its older configuration that can be expressed as the magnitude and direction of change that occurs due to growth at each biologic locus. This paper compares the use of various finite-element types (wedges, hexahedra, tetrahedra) in the modeling of the human cranial base for the analytical description of growth.

INTRODUCTION

Understanding the process of craniofacial growth is critical to informed therapeutic intervention of patients presenting with craniofacial anomalies, especially those that constitute growth disturbances. Unfortunately, the 3D morphological changes of an organism that occur as a result of the growth process remain difficult to describe and even more difficult to quantify.

In the past years we have focused on the analysis of growth in children affected with craniosynostosis (premature cranial suture closure) using 3D coordinate data from longitudinal CT scans. There are currently several methods available to study change in biological form through time using landmark data, but a genuine consensus regarding the relative merits of these methodologies is lacking.

This study concerns the application of finite-element scaling analysis (FESA), in the study of growth. FESA is a method of comparison based on principles of continuum mechanics and finite element analysis. The ability of FESA to detect regions surrounding landmarks that contribute most to the differences between the forms being compared is critical to understanding the processes underlying form change (e.g. growth, evolution, teratologic mechanisms). FESA quantifies differences between forms at each landmark in terms of the magnitude and direction of change (in 2D or 3D) required to produce the target from the initial morphology. To compare forms using FESA, objects are discretized into contiguous finite elements using landmarks as vertices. Differences between forms are measured in terms of strain at landmarks.

SIMULATION STUDIES

In a previous study vertex-specific strains for 100 simulated elements were correlated with one another to investigate the relative independence of strain measures at the vertices of hexahedral elements (Richtsmeier, et al., 1990). We demonstrated that predictable relationships exist between vertices connected by the element design. The magnitude of the relationships change according to a predictable pattern based on the mathematical relationship between the vertices required by the finite element model. These patterns of association can be accounted for quantitatively in any analysis.

Our simulation studies also indicated that element design can affect local directions of change between forms. We concluded that elements should be designed to encompass relatively homogeneous anatomical areas. Obvious anatomical discontinuities should be used as boundaries for elements and not cross edges of contiguous elements. These findings prompted the investigation of alternate element types and stressed the importance of reviewing competing element designs for the representation of the cranial base.

BIOLOGICAL EXAMPLES

In our first analyses of growth in children with craniosynostosis, we used 2 contiguous hexahedrons to model the cranial base (Richtsmeier, et al., 1991) (see Figure 1) and compared the pre-operative morphology of children with varying forms of synostosis to the case-specific peri-operative configuration. A 2D projection of pre-operative growth of the cranial base of a child with metopic synostosis modeled by 2 hexahedral elements is shown in Figure 2. Critical observations from the 3D analysis include: 1) little or no growth along the anteroposterior (Y) axis but a disproportionate amount of growth along the superoinferior (Z) axis for landmarks of the anterior cranial base (1,2,3,4); and 2) relatively greater

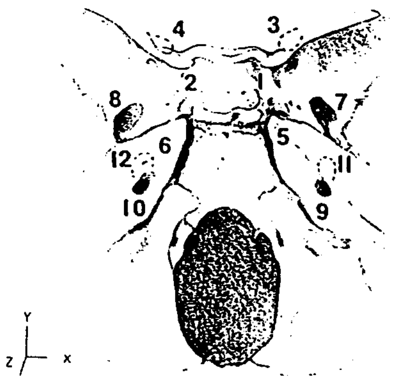

Figure 1. *Twelve landmarks located on a superoposterior view of the cranial base of a normal individual. Landmarks 3,4,7,8,11 and 12 are situated further away from the viewer on the Z (superoinferior axis). Landmarks 3,4,11 and 12 are indicated by dotted lines as they are not visible from this view on an actual skull. Landmark identification: 1,2=right(R), left(L) anterior clinoid process; 3,4=R,L superior orbital fissure; 5,6=R,L petrous intersection; 7,8=R,L foramen ovale; 9,10=R,L internal acoustic meatus; 11,12=R,L carotid canal.*

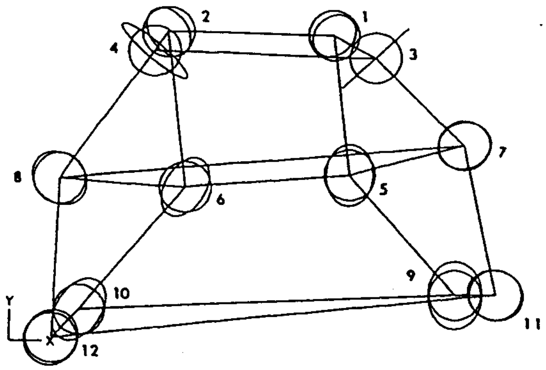

Figure 2. *3D deformation of pre-operative into peri-operative morphology of cranial base in a patient with metopic synostosis as projected onto XY plane using two contiguous hexahedral elements. Orientation mimics that shown in Figure 1. Y is the AP axis, X is the ML axis and Z is the SI axis. Circles centered on landmark indicate the condition where no change occurs between the initial and target configuration. Ellipses superimposed over the circles indicate the direction and magnitude of change due to growth at each landmark.*

magnitudes of growth local to the landmarks of the posterior cranial base (9,10,11,12), most of it occurring along the superoinferior (Z) and anteroposterior (Y) axes.

Figures 3 and 4 model the same cranial base but use tetrahedrons and wedges allowing the incorporation of more biological landmarks than were permitted when hexahedrons were used exclusively. Additionally, the varying element types permit more realistic modeling of the irregular morphology of the cranial base.

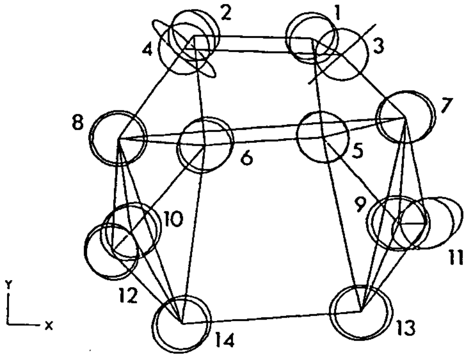

Figure 3. *Superior view of 3D change in form due to growth of cranial base as projected onto the YX plane. Finite-element model uses a hexahedron, a wedge and 4 tetrahedrons. Two additional landmarks are used: 13,14=R,L hypoglossal canal.*

In the comparison of Figures 2 and 3, there is little difference in the directions of growth for the more anteriorly placed landmarks (1,2,3,4,7,8). However the addition of 2 landmarks (13,14) to this model affects the *direction* of change at points 9 and 11 as projected onto the XY plane (Fig 2). Directions of growth viewed on the YZ and XZ planes (not shown here) are unchanged. Though *magnitudes* of local change differ between the 2 finite-element models, the *pattern of relative magnitudes* of local change among the landmarks remains stable.

The finite-element model presented in Figure 4 includes the 12 original landmarks and 6 additional ones. Differences in directions and magnitudes of growth between Figures 2 and 4 are obvious local to the anterior-most points (1,2,3,4) as projected onto the XY plane with all other landmarks showing good correspondence between the 2 finite element models. Comparison of the deformations projected onto the YZ and XZ planes (not shown here) correspond closely for the landmarks used in both models.

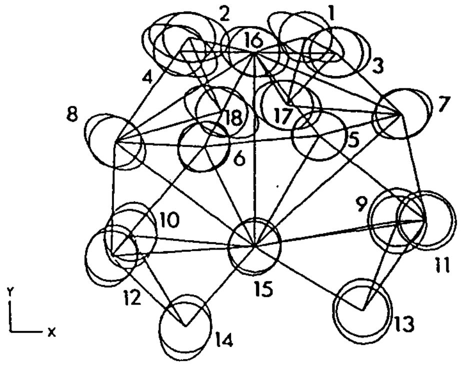

Figure 4. *Superior view of 3D change in form due to growth of cranial base as projected onto the YX plane using 9 tetrahedral elements. Four additional landmarks are used: 15=basion; 16=vomer-sphenoid junction; 17,18=R,L posterior clinoid process.*

Although local differences in directions of change due to growth occur between the three finite-element models, the critical observations of preoperative growth noted above are supported by each model, and the general biological interpretations of growth in the regions surrounding landmarks 1 to 12 do not vary between analyses. Differences in local growth between the 3 models result from the additional anatomical information (landmarks) included in Figures 3 and 4. Exclusive use of hexahedra limited our design and prevented the use of landmarks that could not accommodate a six-sided form. The use of various element types allows the inclusion of more biologic information (landmarks) and the construction of finite-element models that more realistically reflect the morphology of the cranial base. These features enhance the explanatory power of the analysis.

CONCLUSION

When better detail is needed in the application of finite-element analysis, the engineer can further discretize an object using progressively finer meshes. In FESA, meshes are dependent on the identification of biologic landmarks that serve as vertices. We are limited by the landmarks that can be accurately identified and reliably located on the forms of interest. A biologically informed discretization of the object that follows anatomical boundaries, uses all available landmarks, and matches anatomical surface contours to appropriate geometric shapes is critical to the successful application of this method in growth analyses. Evaluation of contrasting element designs should be a part of any FESA of biological form and its variation.

ACKNOWLEDGEMENTS

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