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Numerical Model of Growth Associated with Epiphyseal Plate Loading

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Abstract: ***Growth is a very important subject where many other important decisions are based upon. Numerical simulation presents an indispensable tool to comprehend the in vivo model. we want to present a numerical model that represents the endochondral growth route. The model yielded an increase in volume after cyclic load. The current model could be implemented in the other models.***

Keywords: Epiphyseal plate, Endochondral ossification, Biomechanics, FEA, Bioengineering

1. Introduction

Elongation of the long bones are done by the increase in the size of the tissue resulted from the activity of the chondrocytes [1]

Mechanical loading is an intrinsic part of the cellular pathway that led to this increase.

Although tension had been claimed to enhance chondrocyte action and compression result in opposite action the experimental setting mostly reproduce part of the in vivo environment and both compression or tension should be understood in the cyclic loading rather than pure tension or compression [2]

The establishment of the shape of the bone, namely morphogenesis is passing through a different pathway.

Many events during long bones growth should be understood in the context of other structures formation, namely muscle development. [3]

We agree that the growth of the bone is associated with chondrocyte hypertrophy, but this hypertrophy should not be represented as the prime or sole factor to the growth but rather an event coexist in the context of the total process.

Zones of the long bone in the vicinity of the epiphyseal plate had a well-arranged stiffness gradient. [4]

Stiffness gradient should be held in the mind of any biomechanical researcher.

No clear-cut mechanism that represents the mechanical transduction at the epiphyseal plate

The cartilage at the epiphyseal plate could be regarded as the mold for apposition of the bone matrix main ingredient, namely collagen fibers that get the best chance of best orientation due the highly magnified mechanical strains and displacement at the epiphyseal region. [5]

What we had called reciprocation is a very sound mechanical concept that could fit the purpose of explaining the growth.
Although we had in early stages of the growth multiple cartilaginous centers, only one cartilaginous region will continue till the end where maturity begin. [6]

These regions are necessary to be complex 3D end of the bone, namely joints.

It is highly agreed that the current computation models used in the numerical simulation had many deficiencies that preclude the utilization in simulating all the growth period. [7]

Our main assumptions are.
- Prescence of modifiable region although we assume this changes vi material plasticity but in reality, it is affected by cellular arm. It could be in reality having some sort of plasticity, but it remains cellular controlled.
- Arrangement of the regions that amplify the loading at the epiphyseal plate.

2. Methods

Our model is a simple model with the simplest geometric configurations that facilitate tracking in the shape. The mechanical properties of the model were pure plastic apart from the epiphyseal plate where it had been postulated as elastoplastic material. The loading of the model was in one direction then the loading was reversed. The result was compared to the original model.

The model was built in SolidWorks 2023 (Dassault Systèmes) and simulated in Altair Simsolid 2023 (Altair Engineering)

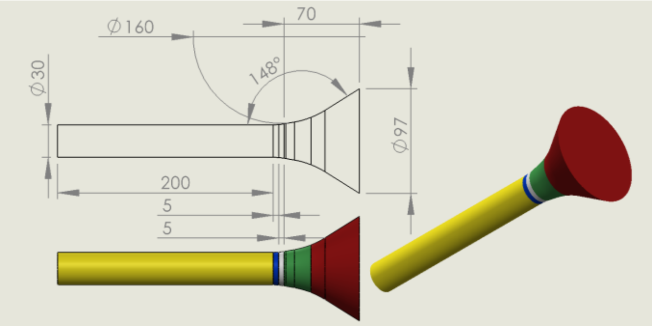

Figure 1: The bone had been modeled as simple engineering domain

We had done multiple pieces for further deeper analysis. Further analysis could be done in detail.

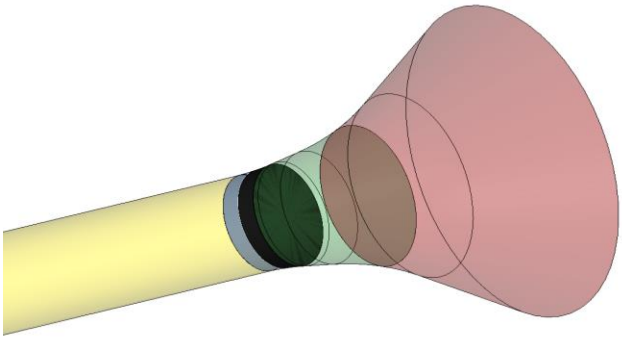

Figure 2: Some region had been segmented to further analyze the results separately.

The black region represents the epiphyseal plate. The stress strain curve for the assigned material used to represent that plate was.

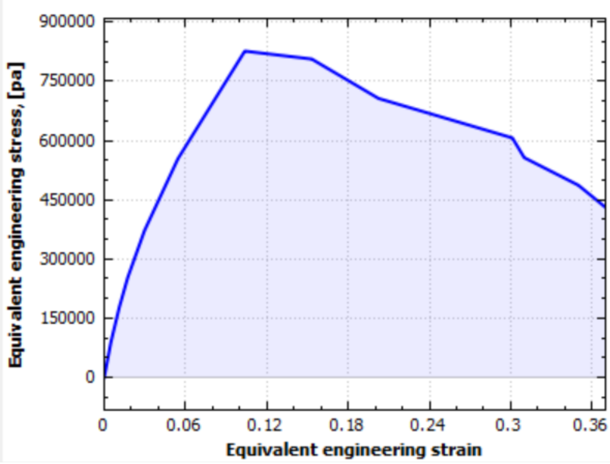

Figure 3: The cartilage was represented as elastoplastic material

Mechanical properties		
Elasticity modulus	1.8040000000e+07	[pa]
Poisson's ratio	3.0000000000e-01	[dimensionless]
Density	7.8500000000e+03	[kg/m^3]
Ultimate tensile stress	6.5000000000e+08	[pa]
Tensile yield stress	9.0200000000e+04	[pa]
Compressive yield stress	9.0200000000e+04	[pa]
Default failure criterion	Von Mises Stress	

Figure 4: For cartilage this is the mechanical properties.

Mechanical properties		
Elasticity modulus	2.3000000000e+10	[pa]
Poisson's ratio	3.0000000000e-01	[dimensionless]
Density	7.8500000000e+03	[kg/m^3]
Ultimate tensile stress	6.5000000000e+08	[pa]
Tensile yield stress	4.2500000000e+08	[pa]
Compressive yield stress	4.2500000000e+08	[pa]
Default failure criterion	Von Mises Stress	

Figure 5: For bone this is the mechanical properties.

This is the first time such an approach has been implemented according to our knowledge. We have chosen the displacement criteria to show the proposed pattern of growth. Most of the other criteria are of limited usage due to the paucity of our knowledge about this anatomical domain. What is supposed to be the distal end of the numerical femur had been rigidly stabilized. A total force of 75 newtons had been applied as a lateral force in the X direction.

The material of the plate had elastoplastic properties and the bone had elastic properties to restrict the changes to the epiphyseal plate and accentuated the changes. Although we had chosen a higher value of the modulus of elasticity resulting in stiffer bone, the proposed effect met the highest tension due to the well-known orthotropicity of the bone.

3. Results and discussions

Bone growth as we suggest had 2 phases.

- Genetics determine the phase where primary bone is built prior to the muscle formation.
- Load driven phase where the bone starts to receive muscular loadings.
- Halting of the bone growth and ossification of the epiphyseal plate is controlled by the stiffness which is determined genetically.

Although we agree that this process is much more complex but the longest phase, where the epiphyseal plate is responsible for the establishment of the total length of long bone should gain specific attention as it involves.

- Same process in the same tissue that continue unchanged for long period of time with nearly the same dimensional configuration, or at least with good proportionate dimensions, if it energy it will had more uniform enlargement
- This tissue, namely epiphyseal plate, will have very strict control with ultimate chronological timing controlled by genetic and stiffness.
- The mechanical boundary conditions will be consistent as the muscular origins and insertions will be very stable.
- Mobile connections, namely joints, are highly constrained suspension systems where modeling them as simple hinged connections is highly erroneous representation.

In this paper we want to shed light on this period of time and make a numerical model with high fidelity.

We should agree that there is no single numerical model that could fit all the phases of development, as it highly biologically controlled process and the mechanical properties of the tissues changing during transition between phases with changes in the boundary conditions.

So, it is better to divide the growth period into phases and numerically simulate each stage or phase individually.

Phases with more biological control and less dependence upon the mechanical loadings are more difficult to be computed as the input will be highly simplified. While the phases with more involvement of the mechanical stimulation could assume more straightforward simulation

Here we are supposing a new approach that partially demonstrates the endochondral ossification route which is standing behind most bones' growth as well as long bones elongation. We had prepared a simple model that represents a long bone, we supposed it the proximal part of the femur. We had assigned elastic properties to the parts of the ossified parts and elastoplastic properties to an intermediate region. We had created a cycle of loading and deloading then observed the results. A comparison of the resultant models with the original model has been made.

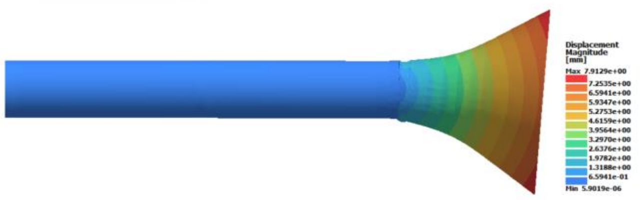

Figure 6: Elastoplastic full load

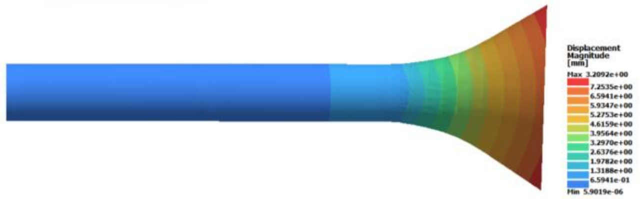

Figure 7: Elastic deformation

The difference between plastic and elastic is evident. Staged damage should be considered in all living tissues creating extremely difficult conditions to be numerically simulated. This difficulty is just on the linear static scale, while nonlinear dynamic simulation has myriad difficulties on a scale that humanity may need at least 250 years to be able to represent.

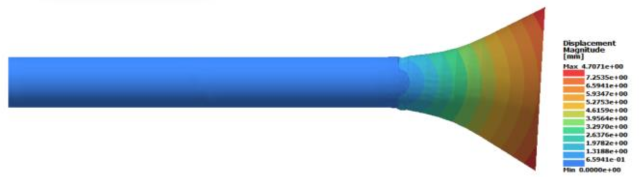

Figure 8: Displacement after unloading.

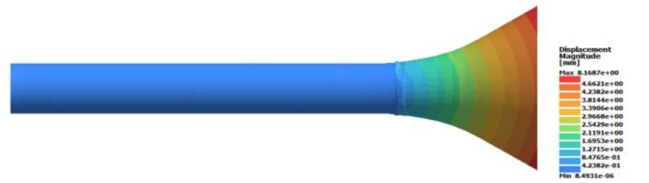

Figure 9: The previous model that resulted from the final unloading changes had been simulated with force on the -X direction. This is elasto-plastic changes.

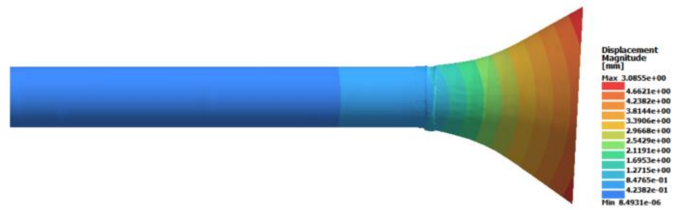

Figure 10: Elastic changes of the returning to initial status condition on the -X direction.

Figure 11: Displacement after unloading. You could recognize the deformation of the epiphyseal plate easily. Our knowledge about this change is nil in the human being.

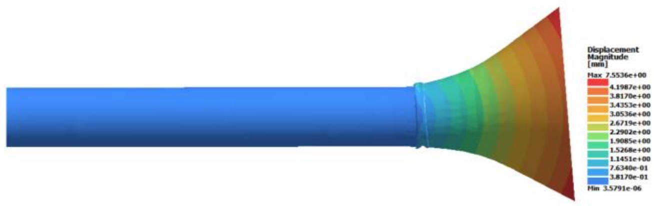

Figure 12: We had reversed the force and do a new deformation in an opposite direction to the initial deformation, and this is the resultant elastoplastic deformation.

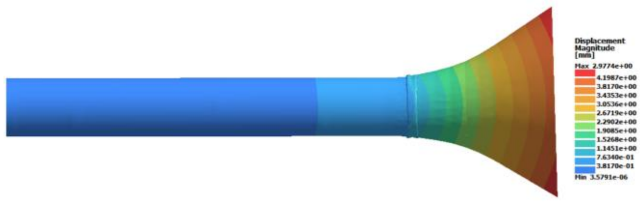

Figure 13: Elastic changes of this in the -X applied 75 newtons.

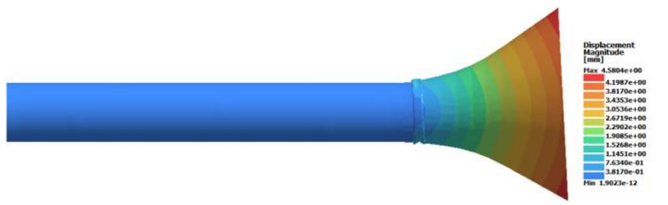

Figure 14: The remaining displacement after unloading. To complete the full cycle we had to return the model to its original position with 75 newtons in the +X direction.

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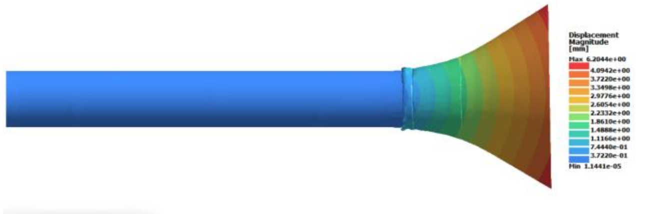

Figure 15 This is the elastoplastic changes after final +X direction 75 newtons applied force.

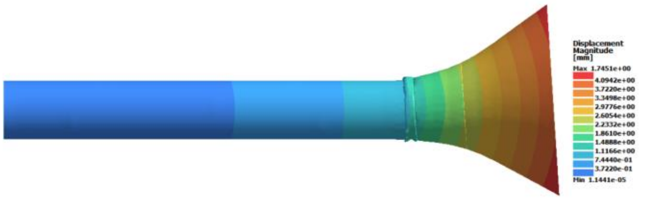

Figure 16 This is the elastic changes after final +X direction 75 newtons applied force.

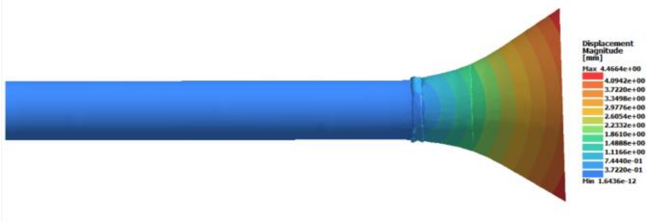

Figure 17 The model hadn't returned to its final position.

In the successive load application, the epiphyseal domain had been deformed resulting in unresolvable model, we had solved this by rematching it and make an offset by 0.2 mm which had an increased at the periphery only due to the trimming on the upper and lower model by the remaining body itself. We don't think this has a significant effect on the result although such a step is better to be studied isolatedly.

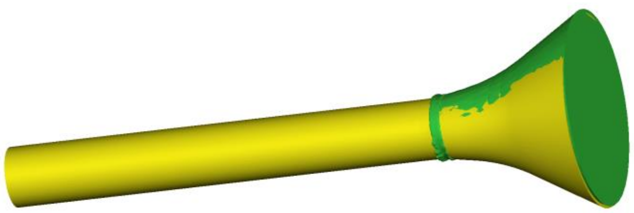

Figure 18: The model of the original CAD with the final model had been drawn. These models don't show objective comparison.

Figure 19: Comparison of the final deformation remained after unloading with the original input CAD

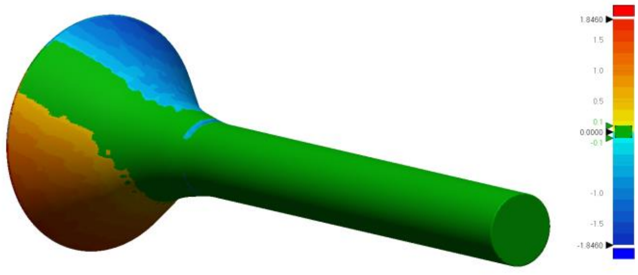

Figure 20: Other view of the comparison.

The validation between the numerical and the real physical model should be done or at least considered by all the researchers in the medical fields. [8] Synchrotron technology could be used to characterize the exact mechanical events in a single loading and unloading cycle. There's a scientific consensus on the need for physiological stimulation to the epiphyseal plate to ensure healthy growth.

As we had complex bone composite on the micro and macro structure, the needed loading should be complex as well [9] The loading condition in our experiment is highly constrained, but actually in reality it is totally different. Joints should be reviewed as compliant component or suspension system rather than simple hinge connection.

Constrain of the limb movement affect the growth due to 2 reasons.

- Limitation of the loads in certain directions and prevent them from occurring in other direction.
- Concentration of them in that restricted direction

This plate should receive multi-planner loads. Movement restraining shoes in high-stress sports could affect patient growth. Rotation preventing shoes actually increases growth plate shear strain due to stabilizing the most distal part of the limb increasing the lever arm tremendously. The plate had very difficult to be modeled strain [10]

Different regions with different mechanical properties of the growth plate had a prime role in determination of the final shape of the bone. The stiffness of the bone will determine the cellular activity and reaching the effect down to molecular level [11]

Cyclic mechanical strain with high-tensile triggers autophagy in growth plate chondrocytes. We think that stiffness is the prime effector of the growth according to Zainab concept. [12] This pattern is also occurred at the endochondral bone growth in the head and neck region, but in a more complex pattern as the bone there had another type of ossification namely intramembranous. Endochondral or intramembranous ossifications are not indicating the initiation process but continued process [13]

We should have a clear view about ossification, whether endochondral or intramembranous, because these two pictures are shown on different occasions, including fracture healing. Without good explanations further knowledge could not be obtained and we enter a vicious circle of futile theories. In the case of craniofacial growth, the intramembranous growth could be derived by the effector the endochondral growth at the base of skull. The increase in the synchondroses junction between the intramembranous driven bone when increased in volume will bring a new volume to the skull base at a very important region. Growth is a sequential process with incremental addition which occurs slowly but in a very precise robust way.

The stiffness that is deriving the growth has not just gradient but could also have different timings making tracking of the growth very difficult. There may be a region where growth stops declaring the start of that in the neighborhood.

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