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Growth plate stress distribution implications during bone development: A simple framework computational approach

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ABSTRACT

Mechanical stimuli play a significant role in the process of long bone development as evidenced by clinical observations and *in vivo* studies. Up to now approaches to understand stimuli characteristics have been limited to the first stages of epiphyseal development. Furthermore, growth plate mechanical behavior has not been widely studied. In order to better understand mechanical influences on bone growth, we used Carter and Wong biomechanical approximation to analyze growth plate mechanical behavior, and explore stress patterns for different morphological stages of the growth plate. To the best of our knowledge this work is the first attempt to study stress distribution on growth plate during different possible stages of bone development, from gestation to adolescence. Stress distribution analysis on the epiphysis and growth plate was performed using axisymmetric (3D) finite element analysis in a simplified generic epiphyseal geometry using a linear elastic model as the first approximation. We took into account different growth plate locations, morphologies and widths, as well as different epiphyseal developmental stages. We found stress distribution during bone development established osteogenic index patterns that seem to influence locally epiphyseal structures growth and coincide with growth plate histological arrangement.

1. Introduction

Long bone embryological development is a complex process that derives from mesenchymal cells that condense and then differentiate into chondrocytes to form a cartilaginous mold. The ossification process starts with establishment of the primary ossification center (POC) in the central part of the future bone or diaphysis [1]. The cartilaginous mold enlarges at both ends of the diaphysis establishing the epiphysis [2]. Toward the end of gestation the secondary ossification center (SOC) forms in the central part of the epiphysis, followed by radial growth until a completely ossified epiphysis is attained [3]. Thus, developmentally long bone epiphyses can first be completely cartilaginous, followed by SOC formation, ending with a completely ossified epiphysis at different stages of human development: gestation, child-hood, and puberty [1–3].

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In the appendicular skeleton cartilage growth tissue remains between the diaphysis and epiphysis in a region identified as the growth plate. Histologically the growth plate is arranged in three zones: reserve, proliferative, and hypertrophic [1,4,5]. This zone is responsible for longitudinal growth and characteristic shape acquisition. Other growth plate characteristics, such as location within the bone, morphology, and width, change according to bone type and age [6]. This is illustrated in the work published by Kandzierski et al. evidencing that the growth plate morphology of a proximal femoral epiphysis can resemble a concave meniscus at the age of four. With increasing age, at seven the growth plate becomes straight, as a ridged non-uniform line. Last, the growth plate assumes the form of an arch at the beginning of puberty [5–10]. In addition, growth plate's width also changes through life, with a wider growth plate during early stages and diminishing progressively until its disappearance toward the end of adolescence [8,11,12]. These changes are controlled by several factors including genetic, biochemical, and mechanical [13]. The latter has been widely recognized as a regulator of growth rate, modifying cell populations in proliferative and hypertrophic states as well as matrix synthesis as evidenced by *in vivo* and *in vitro* studies [14–17].

Various theoretical approaches have been performed in order to understand mechanical regulation. Approaches range from stress distribution analysis within the developing tissue [18–22], to more complex models that integrate biochemical and mechanical factors [23–25]. All of them have only considered events occurring in the epiphysis, not taking into account growth plate characteristics or behavior. Furthermore, up to now stress distribution on the epiphysis and growth plate through different stages of bone development has not been studied.

Using an axisymmetric (3D) finite element analysis we devised a bone with generic geometry to explore stress distribution on the growth plate during different stages of epiphyseal ossification. The aim of this work was to shed light on stress distribution within the growth plate during different stages of epiphyseal ossification, and establish the effect of growth plate morphology on epiphyseal stress distribution and *vice versa*. Results derived from this work will help elucidate mechanical events taking place within the growth plate and epiphysis during long bone growth. Additionally, the information generated may be useful to formulate hypotheses regarding mechanical influences on biological events taking place in normal and pathological bone growth scenarios.

2. Materials and methods

To understand long bone mechanical behavior at different growth stages we performed a computational analysis using linear elastic model solved by fine element analysis (FEA). For numerical analysis a set of partial differential equations was implemented using Fortran (Formula Translating System, New York, USA) programming language. Equation solving and results visualization were performed using ABAQUS v 6.1. and TECPLOT 360 (Tecplot Inc., Bellevue, WA, USA), respectively.

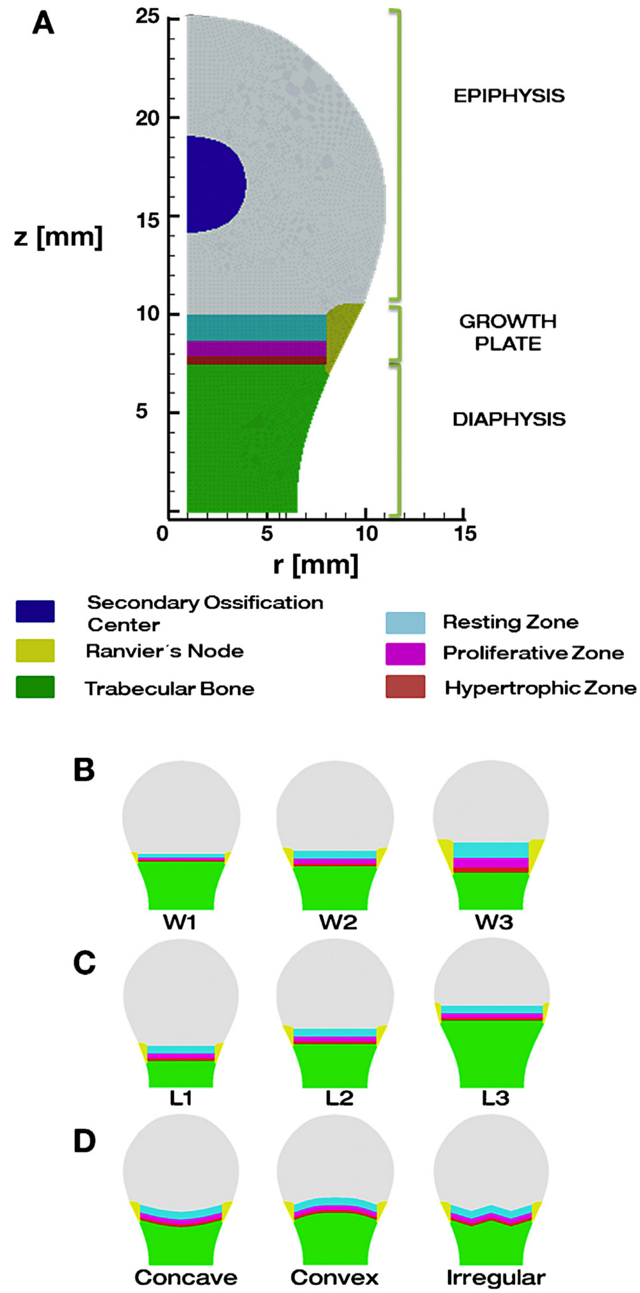

Fig. 1 – Generic bone geometry. (A). Generic bone geometry description and scale. (B and C) Growth plate characteristics. (B) Widths. Representative sample for straight morphology. W1: Thin, W2: Medium, W3: Thick. (C) Locations. Representative sample for straight morphology. L1: Low, L2: Middle, L3: High. (D) Morphologies corresponding to W2, L2.

2.1. *Model*

A 3D axisymmetric model of a generic bone was designed (Fig. 1), taking into account that several human long bones epiphysis have a similar shape during early embryological stages such as the proximal femur head, with bone's longitudinal length of 25 mm and epiphyseal radius of 10 mm (Fig. 1A). For simplification the same morphology was maintained for latter