Biomechanics of the proximal end of the femur during growth

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1. Introduction

Mechanical factors have a strong influence on the growth and development of the skeleton [1], [2]. Forces acting on the growing bones play an important role in their forming process. Disturbances of such loadings in the prenatal period as well as during infancy and childhood can lead to serious developmental deformities [3].

Proximal end of the femur is one of the main parts of the hip joint. The head placed at the end of the neck is the most proximal part of the femur. The axis of the neck is directed superomedially towards the shaft axis in the frontal plane (neck-shaft angle) and anteriorly towards the condylar axis in the transverse plane (anteversion angle). Greater and lesser trochanters are situated at the basement of the neck. Geometry of the proximal end of the femur is very important for the hip joint biomechanics.

During development, growth of the bone is sustained mainly by the chondral epiphyses. Secondary ossification centres, successively occurring in the cartilage, change the structure and biomechanics of the growing epiphyses and lead to forming of the growth plates. In the proximal femur, three ossification centres appear during development: the first is located inside the head, the second occurs in the greater trochanter and the third in the lesser trochanter. Growth plates which insulate trabecular metaphysis from ossifying head (capital epiphyseal plate) and trochanters (trochanteric epiphyseal plates) are active till puberty and allow femoral neck elongation as well as regulation of the neck-shaft and the anteversion angles [4], [5]. The size and shape of the femoral head is formed by activity of the growth cartilage located outside the secondary ossification centre, just below the external layer of articular cartilage.

The aim of the presented research was to perform a biomechanical analysis of the growing proximal end of the femoral bone. Numerical simulation of this structure should allow a better understanding of the bone development in normal conditions as well as in pathological cases.

2. Methods

The finite element method was the main tool used in the research. For the purpose of modelling, an 8-year-old child was chosen. At this age, the structure of the proximal part of femoral bone is very interesting (secondary ossification centres in the femoral head and greater trochanter are present; all growth plates are active). Modelling was performed on the basis of CT-data collected earlier for diagnostic purposes. Left femoral bone, without visible pathological changes, was taken into consideration. CT-data were processed with the use of Mimics software. Finite element discretization was made using ANSYS preprocessor with the use of 3-D 10-node tetrahedral structural elements (SOLID187).

On the basis of the radiological density, all finite elements were initially divided into two distinct groups: cortical and trabecular bone. Afterwards, growth cartilage was modelled. For this purpose, two groups of elements, the first - situated in the central part of the femoral head, and the second - placed at the basement of the greater trochanter, were chosen and new material model was defined for them. The whole epiphyseal part of the femoral head and the proximal part of greater trochanter were modelled as trabecular bone with neglecting cartilage structures. The finite element model was presented in Fig. 1.

![Fig. 1 Proximal part of the of the growing femoral bone (frontal cross-section): a) finite element model, b) reconstruction of CT-data.](image)
Growth cartilage was modelled as a nearby incompressible material, using the hybrid u-P formulation (E=6 MPa, v=0.47). Trabecular and cortical bone were modelled as linearly elastic materials. Isotropic model was used for trabecular bone (E=345 MPa, v=0.3) [6]. Cortical bone was modelled as orthotropic material (Ex=Ey=8 GPa, Ez=14 GPa, Gxy=Gyz=Gxz=3280 MPa, v=0.3) [7].

Distal end of the model was fully constrained. Joint force was applied on the surface nodes of the femoral head. Different joint loading directions were considered in order to analyse regular and pathological conditions. Additional loadings were applied to the greater trochanter in order to model adductors activity.

3. Results

Stress and strain patterns were calculated for particular loading conditions. For all cartilaginous elements, the “growth index” (GI) expressing the intensity of mechanical stimulation of the endochondral growth was calculated using the Carter’s approach [1] (Fig.2):

\[ GI = \sigma_S + 0.5\sigma_H \ [N/m^2] \]

where: \( \sigma_S \) - octahedral shear stress, \( \sigma_H \) - hydrostatic stress.

Fig. 2 Pattern of the “growth index” for regular loadings [8] (calculated only for growth cartilage).

4. Discussion

The mechanical influences on the endochondral bone growth are well documented in the literature. Results obtained in the presented research clearly indicate on the possibility of developmental deformity of the proximal part of the femoral bone in case of the disturbance of loadings. This phenomenon can be used to explain improper orientation of the femoral neck (varus or valgus deformity, increased or decreased anteversion) as well as malformation of the femoral head.

Special attention should be paid to the forces acting on the greater trochanter because the activity of the trochanteric epiphyseal plate has a strong influence on the risk of valgus deformity. Numerical simulation makes it possible to forecast the probable bone deformity in case of abnormal mechanical loadings. It can be useful in the planning of treatment for children with neurological disorders when muscle activity can be disturbed.

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References