# Analysis of the stress and strain in hip joint of the children with adductors spasticity due to cerebral palsy

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Mechanical factors have a strong influence on the development of the musculoskeletal system. Muscle forces are one of the most important sources of the loadings acting on the bone elements and any disturbances in their activity can lead to severe pathology. Cerebral palsy is an example of such a situation and hip joint deformity, leading to its dislocation, is one of the most serious complications accompanied with muscle spasticity.

The aim of the study is to perform an analysis of the stress and strain in hip joint of the children with the imbalance in muscle forces due to adductors spasticity (overactivity). Finite element model has been developed based on anatomical data obtained from computer tomography. The results of numerical simulations show an increase in stress and strain occurring in the femoral head and acetabulum as well as some relocation of its concentration zone in the medial direction.

Key words: *hip joint, cerebral palsy, numerical simulation, stress, strain*

## 1. Introduction

The present form of a skeletal system, especially during growth period, should be treated as an actual effect of the whole osteogenesis process. Many factors can affect its course; one of the most important is the state of mechanical loadings [1]. Disturbances of the physiological forces acting on the growing bone can lead to the deformity of particular elements of the skeleton, and finally, to the pathology of the whole musculoskeletal system. Cerebral palsy is a well-known example of such a situation. The International Working Group on Definition and Classification of Cerebral Palsy has defined cerebral palsy as: "a group of permanent disorders of the development of movement and posture, causing activity limitation, that are attributed to nonprogressive disturbances that occurred in the developing fetal or infant brain" [2]. It is important to emphasise that despite lack of changes (with age) in the brain injury, musculoskeletal disorders are usually distinctly progressive. As a consequence of neurological dysfunction, muscle activities are disturbed (spastic, flaccid or mixed paralysis),
and as a result the loadings acting on the skeletal system are abnormal.

Hip joint deformation is one the most serious complications occurring in children with cerebral palsy. It is supposed that due to imbalance in muscle forces, the originally well formed joint becomes decentred, subluxated and finally dislocated. Spasticity of adductors, flexors and iliotibial tract is usually mentioned as the reason for such pathological development [3].

The main aim of this study is to establish a numerical modelling of the children's hip joint and to find the differences in strain and stress caused by adductors spasticity.

## 2. Methods

### 2.1. Geometrical model

Numerical modelling, based on the finite element method, was used to calculate stress and strain pat-

terns. Geometrical, three-dimensional (3D) model of the children's hip joint was built based on computer tomography (CT) data [4], collected from a fourteen-year-old girl suffering from cerebral palsy (figure 1). The right hip joint (proximal part of femur and acetabular fragment of pelvis), without visible bone deformity, was taken as the object to be modelled. The range of model was influenced by CT data extension. The choice of undeformed joint serves our purpose (at the present stage of research) of finding the primary reason for the bone deformity.
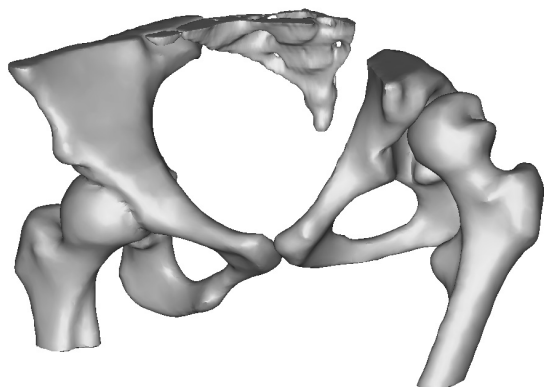


Fig. 1. Three-dimensional reconstruction of CT-data collected from a fourteen-year-old girl.
Left hip joint deformed due to cerebral palsy

CT data initially written in the DICOM file were processed using MIMICS v.11 software (*Materialise, n.v.*). Outer boundaries of bone elements were separated and triangular mesh was generated on their surface. Afterwards this model was imported into finite element software (ANSYS v.11, *Ansys Inc.*). Based on this surface mesh, a three-dimensional, volumetric model consisting of solid finite elements was developed (figure 2). The whole inner space surrounded by external surface was filled in. Internal structure of

bone elements (e.g. marrow cavity) was neglected in this stage of modelling.

## 2.2. Material properties modelling

Finite element model, generated with volumetric mesh, was imported once again into MIMICS. Material properties were defined individually for each element, based on radiological density [5], and in this way a non-homogeneous, isotropic material model of bone tissue was developed. For trabecular bone the relationship between the Hounsfield scale *HU* and the apparent density $\rho_a$ was defined as follows:

$$\rho_a = 0.17 + 0.0012\,HU. \tag{1}$$

Compressive (Young's) modulus $E$ [MPa] was evaluated using the following formula:

$$E = 1.31 \cdot \rho_a^{1.4}. \tag{2}$$

For the elements located in the marrow cavity, Young's modulus approaching zero was assumed. Constant value (0.3) of Poisson's coefficient was taken for all elements. Young's modulus for cortical bone was increased to the value between 10–16 GPa, according to the local radiological density.

## 2.3. Loading conditions

There are many muscles which affect the hip joint movement. Their contractions, controlled by nervous system, should counterbalance the gravity of the upper body and ensure the possibility of leg movement. One can find many models of muscle forces equilibrium, proposed by, e.g., BĘDZIŃSKI [6] or BERGMAN [7]. Unfortunately, all of them are of poor use in the case
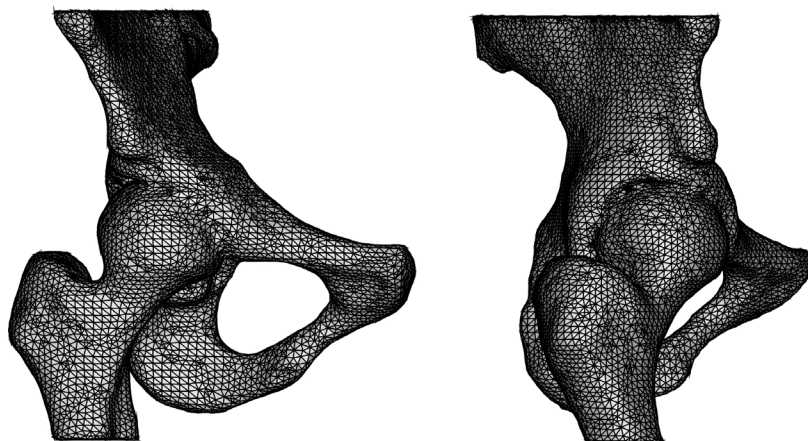


Fig. 2. Finite element model of the children's hip joint prepared on the basis of CT-data

of cerebral palsy, because, both in spasticity and in flaccid paralysis, muscle activity does not correspond to static or dynamic equilibrium.

In order to analyse the influence of adductor overactivity on hip joint biomechanics, two loading models were developed. Six muscles were taken into consideration: adductors (longus, brevis and magnus), abductors (gluteus medius, tensor fasciae latae) and flexor (rectus femoris). It should be emphasized that, in general, much more muscles can be used for movement in the hip joint, which was neglected in the present study. Making comparative analysis of adductor – abductor equilibrium it is possible to assume that the activity of other muscles is constant and does not interfere with the changes of stress and strain patterns due to adductor spasticity. Rectus femoris was taken into consideration only in order to overcome the lack of equilibrium in sagittal plane due to asymmetrical location of adductors and abductors in A-P direction.

Static equilibrium of abductors and adductors was assumed at first. Based on the geometrical model described above, the location of particular muscle forces was defined in 3-D space (figure 3) and their arms were measured using CAD software.

Taking into consideration the anatomy of muscles, their cross-section areas and physiological observations [8] it was assumed that the forces generated by both abductors are equal to one another:

$$F_{GM} = F_{TFL}, \qquad (3)$$

where:

$F_{GM}$ − the force of gluteus medius,
$F_{TFL}$ − the force of tensor fasciae latae.

In order to illustrate the anatomical differences between particular adductors [8], the following assumption was made:

$$F_{AM} = 2F_{AL} = 3F_{AB}, \qquad (4)$$

where:

$F_{AM}$ − the force of adductor magnus,
$F_{AL}$ − the force of adductor longus,
$F_{AB}$ − the force of adductor brevis.

To make the resultant force acting in the hip joint close to its physiological value (more than twice greater than the gravity) the following data were assumed:

$$F_{AM} = 75\,\text{N}, \quad F_{AL} = 37.5\,\text{N}, \quad F_{AB} = 25\,\text{N}. \quad (5)$$

Solving the equation of the equilibrium of moment of forces

$$\sum_i M_{iy} = F_{AL} r_{AL}^{ZX} + F_{AB} r_{AB}^{ZX}$$

$$+ F_{AM} r_{AM}^{ZX} - F_{GM} r_{GM}^{ZX} - F_{TFL} r_{TFL}^{ZX} = 0, \qquad (6)$$

where: $r_{AL}^{ZX}, r_{AB}^{ZX}, r_{AM}^{ZX}, r_{GM}^{ZX}, r_{TFL}^{ZX}$ are the arms of the forces for (respectively) adductor longus, adductor brevis, adductor magnus, gluteus medius and tensor fasciae latae (directions *x*, *y*, *z* presented in figure 3), and taking into consideration assumptions (3) and (4), it was possible to calculate the values of abductors forces:

$$F_{GM} = F_{TFL} = 91\,\text{N}. \qquad (7)$$

To overcome the imbalance of forces in sagittal plane, tension of rectus femoris ($F_{RF}$ = 260 N) was
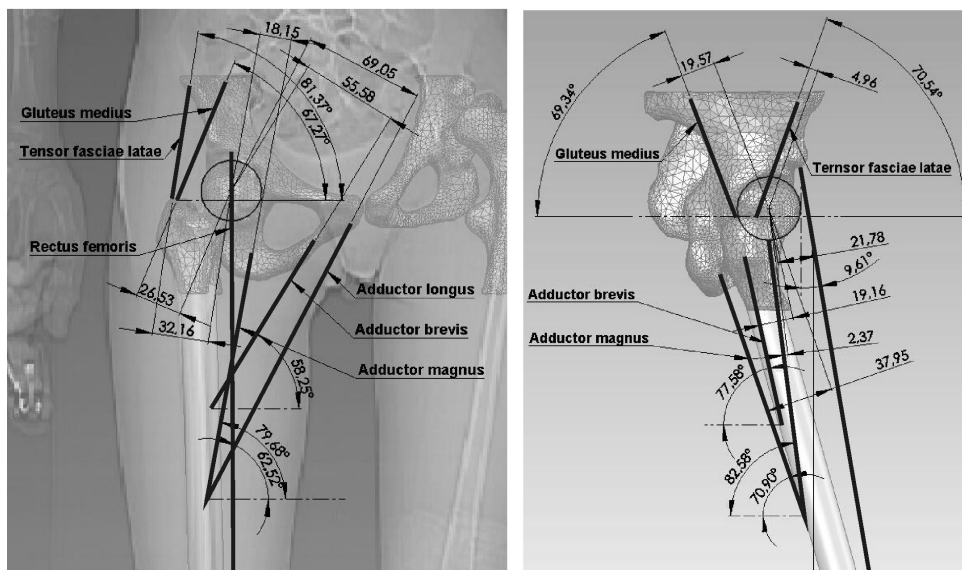


Fig. 3. An analysis of muscle forces acting on the hip joint in 3-D space. Arms and angles of action of particular muscles were calculated based on the geometrical model reconstructed from CT-data

calculated by solving the equation:

$$\sum_i M_{ix} = F_{AL} r_{AL}^{YZ} + F_{AB} r_{AB}^{YZ} + F_{AM} r_{AM}^{YZ}$$

$$+ F_{GM} r_{GM}^{YZ} + F_{TFL} r_{TFL}^{YZ} - F_{RF} r_{RF}^{YZ} = 0. \qquad (8)$$

Loading conditions presented above allowed the stress and strain occurring in the hip joint without any musculoskeletal disability (muscle forces were in equilibrium) to be calculated. The results obtained using this model would be taken as a reference point in analyzing the influence of adductor spasticity (overactivity). In this case, the values of adductors forces were increased twice:

$$F_{AM}^{S} = 150 \, \text{N}, \quad F_{AL}^{S} = 75 \, \text{N}, \quad F_{AB}^{S} = 50 \, \text{N},$$

where $F^S$ is the muscle force in the case of spasticity.

All other loadings remained unchanged.

All the nodes located at the distal end of the femur model were fully constrained. The model of the pelvis was entirely connected with femoral head, according to the CT-data reconstruction. Non-homogeneity of the material in the contact area (bone and cartilage) was approximated by different material parameters assumed for particular elements.

During one leg standing, pelvis is stabilized in relation to femur only by tension of muscles and ligaments. The model of pelvis should then remain unsupported when the distal end of femur is fixed. However, for ensuring numerical stability of the model any support of the pelvis is necessary and for this reason the symmetry conditions are modelled at the group of nodes in the area of pubic symphysis. No support is modelled in the region of sacroiliac joint.

# 3. Results

Taking into account the aim of the present study and the fact that the most important thing is to evaluate the influence of adductor overactivity, both stress and strain will be presented on the cross-section of the model, being similar to frontal plane (figure 4).

Equivalent stress and strain patterns, calculated for the model with the muscle forces in equilibrium, are presented in figures 5a and 6a, respectively. Similar results, obtained for the model with adductor dominance, can be seen in figures 5b and 6b.
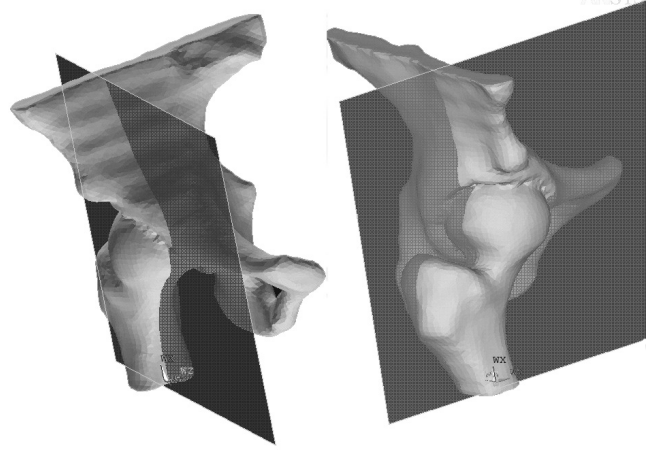


Fig. 4. Cross-section plane used for stress and strain analysis



$$\sigma_{eqv} = \sqrt{\frac{1}{2}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right]}$$
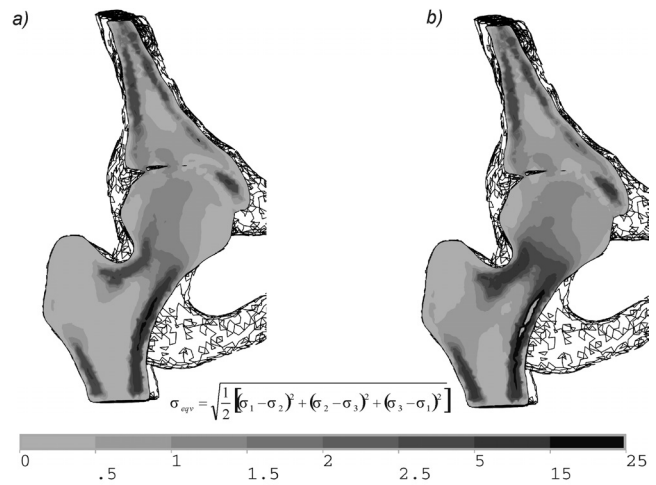
0 .5 1 1.5 2 2.5 5 15 25

Fig. 5. Equivalent stress patterns (MPa) in the children's hip joint: a) under the loading of muscle forces, when the equilibrium conditions of adductors and abductors are satisfied, b) in the case of adductors spasticity (overactvity)
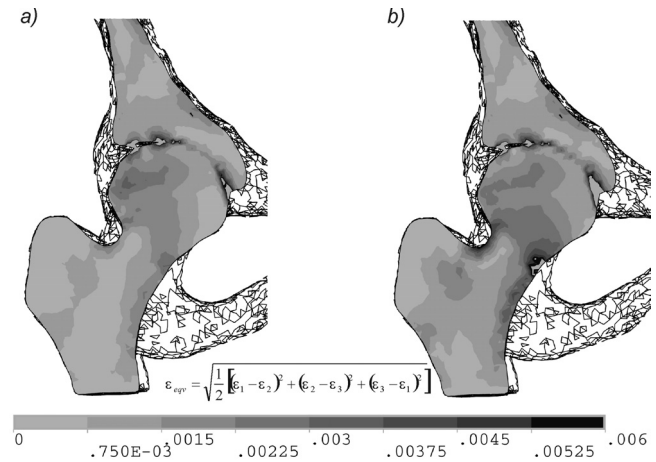


$$\varepsilon_{eqv} = \sqrt{\frac{1}{2}\left[(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2\right]}$$

0 .750E-03 .0015 .00225 .003 .00375 .0045 .00525 .006

Fig. 6. Equivalent strain patterns (–) in the children's hip joint: a) under the loading of muscle forces, when the equilibrium conditions of adductors and abductors are satisfied, b) in the case of adductors spasticity (overactvity)

Comparing both sets of results it is possible to state that the values of equivalent stress and strain are greater in the case of adductors overactivity. This is understandable; we must remember, however, that total loadings in this case are higher due to increase in adductor tension.

Another, probably more important, observation is some relocation of the stress/strain concentration zone in the medial direction.

To make the analysis easier, the coefficient of equivalent stress/strain changes was calculated (figure 7). In figure 7, the values obtained for spasticity were divided by the appropriate values obtained for normal loading. This figure clearly shows that in the case of spasticity, the medial part of the joint is heavily overloaded, whilst the lateral one in unloaded.

$$\sigma_{eqv}^{S} \big/ \sigma_{eqv} = \varepsilon_{eqv}^{S} \big/ \varepsilon_{eqv}$$



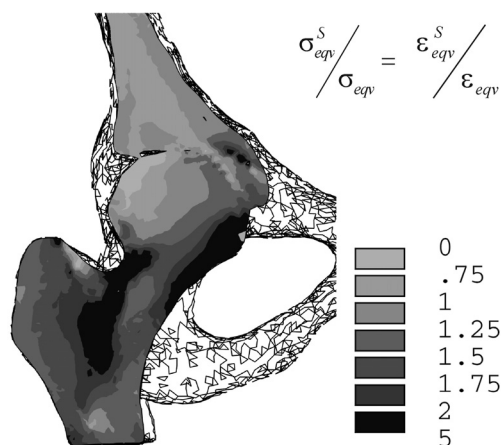| | |
|---|---|
| | 0 |
| | .75 |
| | 1 |
| | 1.25 |
| | 1.5 |
| | 1.75 |
| | 2 |
| | 5 |

Fig. 7. The changes of equivalent stress and strain patterns due to increase in adductors tension: the value under 1 – region with decreased stress and strain, the value over 1 – region with increased stress and strain

# 4. Discussion

It is obvious that in effect of the changes in loadings acting on the hip joint, some disturbances in the stress and strain patterns appearing in the bone structure can occur. The results of numerical analysis presented above can only confirm this statement. However, we are still faced with an unanswered question about the final effect of such stress and strain changes. It is well known that bone tissue undergoes a continuous process of remodelling and has the ability to adapt its internal structure to mechanobiological conditions. This problem is widely discussed in the literature and now will be omitted. It seems that another problem is even more important in the case of hip joint in children with cerebral palsy; one must remember that

children suffer from deformity of hip joint element at the age when intensive body growth process takes place [3]. CARTER et al. [1] described the influence of mechanical factors on the skeletal growth. SHEFELBINE and CARTER [9] made some numerical simulations, where the changes of loading acting on the bone structure allowed the development of hip joint deformity to be explained. A mechanical stimulation of growth plate activity can play, in such situations, the most important role.
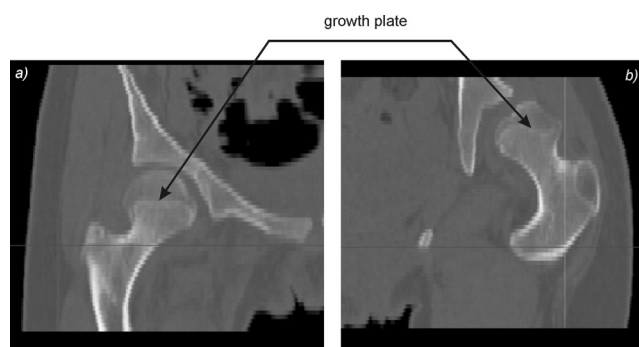


Fig. 8. Radiographs of children's hip joints with easily visible growth plates: a) anatomically correct shape of growth plate, b) deformity of growth plate in the case of cerebral palsy

Preliminary observation of growth plate morphology (figure 8) shows that in the case of femoral bone head deformed due to cerebral palsy (figure 8b), the shape of growth plate is considerably different from that in the anatomically proper one (figure 8a). Further research is necessary to find any relationship between stress and strain disturbances and growth plate deformity.

## Acknowledgement

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