

## Numerical analysis of damping properties of tissue in lower extremity

Tomasz Klekiel<sup>1</sup>, Grzegorz Sławiński<sup>2</sup>, Romuald Będziński<sup>1</sup>

<sup>1</sup> University of Zielona Gora, Department of Mechanical Engineering, Division of Biomedical Engineering, Zielona Gora, Poland  
email: t.klekiel@ibem.uz.zgora.pl, r.bedzinski@ibem.uz.zgora.pl

<sup>2</sup> Military University of Technology, Department of Mechanics and Applied Computer Science, Warsaw, Poland  
email: grzegorz.slawinski@wat.edu.pl

**ABSTRACT:** This paper presents an analysis of damping properties of a tissue in human lower extremity. The analysis was designated in order to determine probability of an injury risk in a lower limb during high-rate vertical loading such as underbody blast in a military vehicle. A numerical model of a lower limb was developed in order to better understand the process of dissipation energy consisting of two shank bones: Tibia and Fibula, Femur bone and Pelvis plate. Furthermore the articular cartilage was modeled in a knee joint. The stiffness of the model was realized by including ligaments and selected muscles. An analysis of an influence of tissue properties changes on dispersion energy was carried out based on this model. The results were obtained both for stiffness changes of particular elements as well as for characteristics changes of the material models. The calculation data showed a significant effect of a muscle on portion energy transmitted to the pelvis plate. This transmission realized by bones, articular cartilages and ligaments is increased when the muscle has suitable high tension. The changes of muscle tension can change the level of dissipation energy up to 10%. Increasing stiffness of the articular cartilage caused high dissipation of energy nearly up to 20%.

**Keywords:** lower extremity, impulse load, damping, dissipation energy

### 1. Introduction

A knee is one of the best investigated human joints. The numerical models contains, apart from bones also articular cartilages, meniscus and main ligaments: anterior cruciate ligament (ACL), posterior cruciate ligament, middle cruciate ligament (MCL), lateral cruciate ligament (LCL)[1]. Usually, the soft tissues are defined by one-direction link elements. This approach is useful during modeling of ligament kinematic function but does not give possibility to analyze the influence of shear forces on stresses generated in these structures [2-4]. The FEM analysis, in which the ligaments are modeled as 3D body, can be found in papers [5-7] for ACL and MCL[8].

In literature, the models, including lower extremity models, are characterized by: simplified geometry, limited range of movement and simplified model of ligaments and muscles [9]. Early created models were based on very simplified geometry obtained without any imaging method. The material models are assumed with linear elasticity and calculations was realized without friction contact for small deformation. Nowadays, the models [10,11] are prepared based on MRI and CT imaging using the BMD method to define- elasticity properties of a bone related to its density. The contact in joints is defined as frictional and the calculations take into account large deformations. Based on these experiences, a model of lower extremity was prepared in this paper.

### 2. Materials and methods

Fig. 1. presents the lower extremity model which consists of: 1 – Tibia, 2 – Femur, 3 – pelvis plate, 4 – patella, 5 – knee articular cartilage, 6 – articular cartilage of the hip joint, 7 – lateral ligaments, 8 – cruciate ligaments, 9 – joint capsule, 10 – knee flexor muscle group, 11 – extensor thigh muscle group.

The model was used to analyze the process of energy dissipation by structures of soft tissues such as ligaments

and muscles and articular cartilage. In this model (Fig. 1.) a knee structure was exactly reconstructed as the main element damped the energy. The main problem during preparation of this model was connected with the position of the limb. The imaging data from CT relate to an upright limb. For this investigation, a model in seating position was required. Flexion in the knee was achieved manually by suitable positioning of the bones and other tissues.

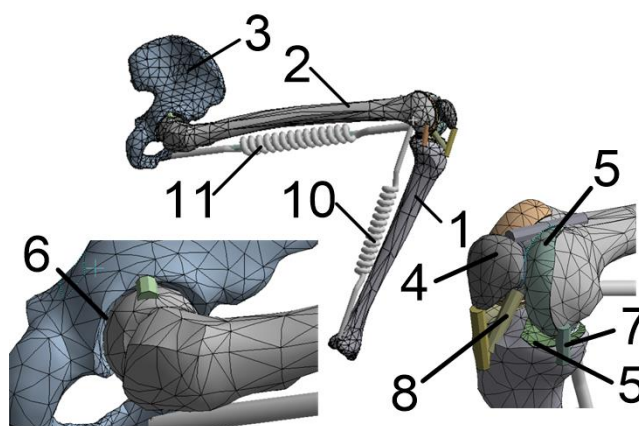


Fig. 1. The finite element model of lower extremity  
a) limb model, b) hip joint, c) knee joint

The bones were modeled as two-phase structures. An external phase is defined as a cortical bone and an internal phase as trabecular structures. For the cortical bone, the Young modulus was equal to 18GPa and Poisson ratio was assumed as 0.3. The trabecular bone was characterized by the modulus equal to 350MPa and Poisson ratio assumed as 0.33. The ligaments were modeled as the link elements with Young modulus equal to 100MPa and Poisson ratio assumed as 0.4. The groups of muscles were defined as spring elements.

The analysis of the muscle stiffness changes was realized for a femoral biceps muscle and a semitendinosus

muscle. These muscles cause the leg extension, where the long head straightens and adducts of the thigh and also flexes the leg at the knee joint, and the short head flexes the shank.

### 3. Results

Fig. 2. presents distribution of stresses in the bones. Concentration of stresses was observed around the head of the femoral bone.

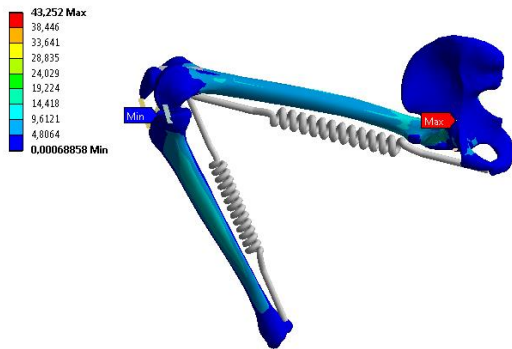


Fig. 2. The map of stresses.

In Fig. 3., distribution of stresses in a profile of the femoral head is shown. Concentration of stresses appears on the external surface of the bone in the cortical structure.

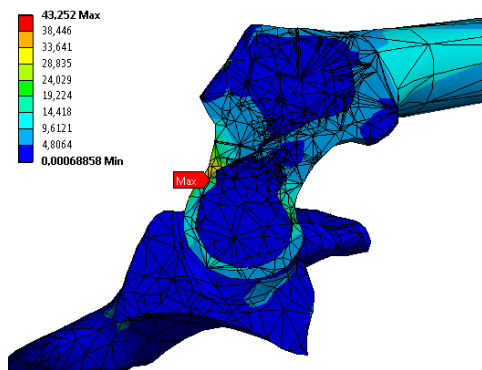


Fig. 3. Map of stresses in head of femur

The maximal stresses of 43MPa are not provided to damage the bone. The bone strength is estimated on 120-160 MPa[12].

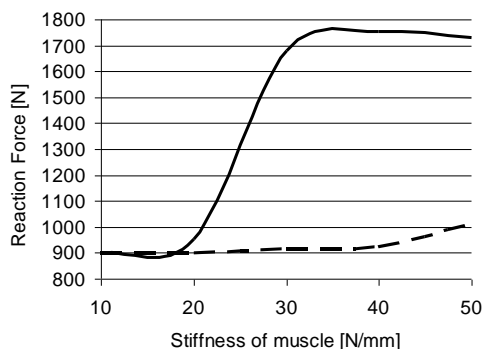


Fig. 4. Relationship between tension of muscle and force of reaction.

Fig. 4. presents the values of reaction force that depends on the change of muscle tension. After crossing the border of some muscle tension, the energy transmitted by model is higher. As a result, the tension which is concentrated in the pelvis increases up to 20%.

### 4. Conclusions

In this paper, the authors present a biomechanical analysis of lower extremity during high vertical dynamic load. The analysis was concentrated on damping energy. The object of investigation was lower extremity of an occupant in a military vehicle under which an IED charge exploded. As a result of explosion, a limb is at a high risk of injury. The probability of injury depends on many factors. The main of these factors are connected to biomechanical characteristics of the particular tissue. In this work, an influence of particular properties on the dissipation energy was examined.

The analysis of energy absorption by the tissues of the limb was realized by calculation of reaction force in a place of support. The place of support was defined in the pelvis plate. The graph (Fig.4.) presents that after some level of muscle stiffness, if the muscle force is increased the reaction force also increases. This phenomenon is due to the fact that the stiffness of the whole model is increased and the contact forces between particular bones are higher. This increasing rigid of the limb causes the increased stresses in the bones, articular cartilages and also in the ligaments which can provide a higher risk of injury.

*This work was financed by the project no. DOBR-BI04/022/13149/2013 granted by NCBiR.*

### References

- [1] Pena E., et. al, *A three-dimensional finite element analysis of the combined behavior of ligaments and menisci in the healthy human knee joint*, Journal of Biomechanics 39 (2006) 1686–1701
- [2] Blankevoort L., et. al, *Ligament-bone interaction in a three-dimensional model of the knee*, Journal of Biomechanical Engineering, 113: 263-269, 1991.
- [3] Bendjaballah M.Z. et. al., *Biomechanical response of the passive human knee joint under anterior-posterior forces*, Clinical Biomechanics, 13: 625-633, 1998.
- [4] Donahue T.L.H. et. al., *A finite element model of the human knee joint for the study of trio-femoral contact*, Journal of Biomechanical Engineering, , 124: 273-280, 2002.
- [5] Liu Wen et. al., *The effect of hamstring muscle compensation for anterior laxity in the ACL-deficient knee during gait*, Journal of Biomechanics 33: 871-879, 2000.
- [6] Roddy K., et. al, *Mechanical Forces and the Development of Shape in The Avian Knee Joint*, 16th ESB Congress, Oral Presentations, Journal of Biomechanics 41, 2008
- [7] Pioletti D.P. et. al., *Viscoelastic constitutive law in large deformations: applications to human knee ligaments and tendons*, J Biomechanics; Vol. 31, pp. 753–757, 1998.
- [8] Gardiner J. C. et. al., *Subject-specific finite element analysis of the human medial collateral ligament during valgus knee loading*, Journal of Orthopaedic Research 21: 1098–1106, 2003.
- [9] Gefen A. *Plantar soft tissue loading under the medial metatarsals in the standing diabetic foot*. Med Eng Phys.,25:491-9, 2003.
- [10] Butz K. D. et. al., *Stress distributions and material properties determined in articular cartilage from MRI-based finite strains*, Journal of Biomechanics 44:2667–2672, 2011
- [11] Wolf P. et. al., *Modeling of the passive mobility in human tarsal gears implications from the literature*, The Foot 14:23–34, 2004.
- [12] R. Będziński, *Biomechanika Inżynierska*, Oficyna Wydawnicza Politechniki Wrocławskiej, 1997