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FINITE ELEMENT PREDICTING OF FLEXIBLE PU FOAM MATTRESS COMFORT

UDOBNOST FLEKSIBILNOG DUŠEKA OD PU PENE PROCENJENA KONAČNIM ELEMENTIMA

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- polyurethane foam
- FEM
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Ključne reči
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- FEM
- udobnost spavanja
- kontaktni pritisak

Abstract

In this paper we generate finite element (FE) models to predict and analyse the comfort of a flexible polyurethane foam mattress with different mechanical properties (compressive strength). We use the half of a symmetrical three-dimensional virtual numerical model of foam mattress and human body in a supine position. Our goal is to analyse the different factors of mattress comfort, as contact pressure peak on the surface between human body and foam mattress, contact pressure distribution on the surface of the mattress, and displacement of mattress in the load direction of body weight. These factors are predicted by numerical simulation. A linear elastic isotropic material model is used for skin, the Mooney-Rivlin material model, which is a mathematical FEM model, is used to simulate hyperelastic behaviour of muscle tissue, and nonlinear hyperelastic materials are used to represent nonlinear compressive strength of flexible polyurethane foam. The results present the effect of compressive strength of FPU foam on the main parameters of mattress comfort. We show the variation of parameters depending on the firmness or softness of mattress foam.

Izvod

U ovom radu smo generisali modele konačnih elemenata (FE) da bismo predvideli i analizirali udobnost fleksibilnog dušeka od poliuretanske pene sa različitim mehaničkim svojstvima (čvrstoća na pritisak). Upotrebili smo polovinu simetričnog trodimenzionalnog virtuelnog numeričkog modela dušeka od pene i ljudskog tela pri spavanju u položaju na leđima. Cilj je da analiziramo različite faktore udobnosti dušeka, kao što su maksimalni kontaktni pritisak na površini između tela i dušeka od pene, raspodela kontaktnog pritiska na površini dušeka i pomeranje površine dušeka u pravcu opterećenja težine tela. Ovi faktori su određeni numeričkom simulacijom. Model linearnog elastičnog izotropnog materijala je upotrebljen za kožu, matematički FEM Muni-Rivlin model materijala je upotrebljen za simulaciju hiperelastičnog ponašanja mišićnog tkiva, a nelinearni hiperelastični materijali su korišćeni za predstavljanje nelinearne čvrstoće na pritisak fleksibilne poliuretanske pene. Rezultati predstavljaju uticaj pritisne čvrstoće FPU pene na glavne parametre udobnosti dušeka. Predstavili smo varijaciju parametara u zavisnosti od čvrstoće ili mekoće pene za dušeke.

INTRODUCTION

Flexible polyurethane foams having low-resilience or 'viscoelastic' behaviour are particularly favourable for applications in several sectors, e.g., bedding, automotive seating footwear, etc., where high foam comfort levels, as perceived by users, and the consistent performance of foam over its lifetime, are required, /1/.

The most common material found in foam mattresses is flexible polyurethane foam (FPF). It can be modified in many ways to adjust the different comfort and firmness grades by varying composition, density, and microstructure of the material, /2- 4/.

The main factors of sleeping comfort are the contact pressure and its distribution. Mattress quality is considered as one of the most essential elements, because the mattress directly contacts the human body. There are many studies that investigate sleeping comfort of mattress that were evaluated using sensory tests and body pressure distribution, /1, 5-13/.

Finite element (FE) model simulations were used to predict the contact pressure between a foam mattress and the human body, and the displacement of mattress in a supine position. Different previous studies use two-dimensional or three-dimensional (3D) FE models to predict contact pressure between the human body and a mattress cushion /14/.

Skin and foam material of mattress are assigned as linear elastic materials, and muscle soft tissue is considered hyperelastic material (Mooney-Rivlin model), /14/. In this context, our model is inspired by the work of Wookjin Lee et al. /14/. Our work is a study on the effect of compressive strength of flexible PU foams used as main materials in mattress construction, analysed to investigate the influence of their mechanical properties on human body comfort levels. Nine mechanical properties (compressive strength) of densities and components proportion have been used in this work /3, 15/, and are assumed as nonlinear compressive strength hyperelastic material model.

FINITE ELEMENT MODEL

Finite element analysis (FEA) is performed on the virtual 3D CAD model of the human body in supine position with a weight of 63 kg and length of 1.67 m, and foam mattress with a length of 1900 mm, width of 600 mm, and height of 250 mm. We simplified the FEM model and use the property of symmetry of the model for minimising the computational and time cost, and the body force of gravity is applied to the human body, /14/, Fig. 1.

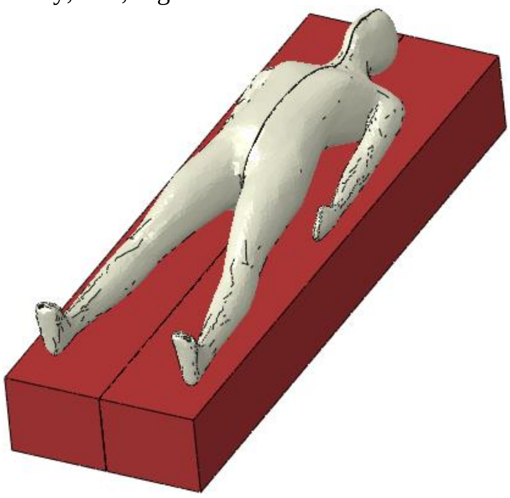

Figure 1. The full human body model laid on the mattress.

The model was solved in one analysis step, the step of loading using static analysis and all loading conditions were static. The generated model does not contain a skeleton /14/. The FEM model was used to predict the parameters of mechanical comfort of the polyurethane foam mattress, such as contact pressure and its distribution between the human body and foam mattress, and the displacement of the foam mattress in the direction of gravity load.

MATERIAL PROPERTIES

Our numerical model includes three main basic materials: skin, muscle, flexible polyurethane foam. The skin is modelled as linear elastic material. Muscle tissues are modelled using the Mooney-Rivlin hyperelastic isotropic material model, /14/. The foam is modelled as a nonlinear elastic isotropic material, /15/. The mechanical properties of both skin and muscle are presented in Table 1. The foam is modelled as a nonlinear elastic isotropic material, /15/.

Table 1. Element information and material properties of the human body used for FEM analyses.

	Skin	Muscle
Element information		
Element type	Linear wedge elements C3D6	Linear tetrahedral element C3D4H
Element size (mm)	15	15
No. of elements	13017	93913
Material properties		
Material model	Linear elastic isotropic	Mooney-Rivlin
Young's modulus (kPa)	0.15	/
Poisson's ratio	0.46	/
Density (kg/m^3)	1100	1060

Material parameters of Mooney-Rivlin model A1, A2, A3, and A4 are defined from the following equation, /14/:

$$W = A1(J1-3)+A2(J2-3)+A3(J2-1)+A4(J3-1)\,,$$

where: $J1$, $J2$, and $J3$ are invariants in the Cauchy-Green strain tensor, and the material parameters $A1$, $A2$, $A3$, and $A4$ are defined as follows:

$A1 = 0.00165$ MPa , $A2 = 0.00335$ MPa , $A3 = (1/2)A1 + A2$,

$A4 = A1(5v-2)+A2(11v-5)/2(1-2v)$,

where: $v = 0.49$.

The compressive strength of flexible polyurethane foam (stress-strain relations) is strongly dependent on three main factors. These factors determine the mechanical properties of foam parts; material type (MDI or TDI), density, and proportion of two main foam components, /4, 15/. However, for this study, the flexible polyurethane foam material used for mattress material is assumed as nonlinear material, hyper-plastic, and the mechanical properties are shown in Fig. 2, where the curves show nonlinear, hyperelastic property /15/. In Fig. 2 we represent the compressive strength (stress-strain curve) of nine FPF materials selected.

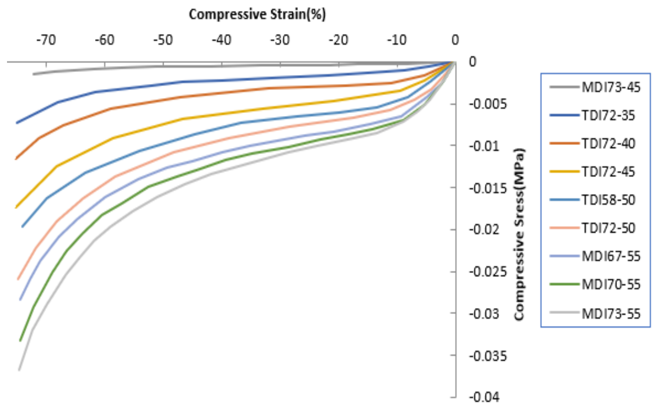

Figure 2. Compressive strength of flexible polyurethane foams.

BOUNDARY CONDITIONS AND ANALYSIS STEPS

While the computational time cost is our constraint, we use the half of symmetry FE human model placed in the supine position on top of the mattress and a mattress width reduced to 300 mm, Fig. 3.

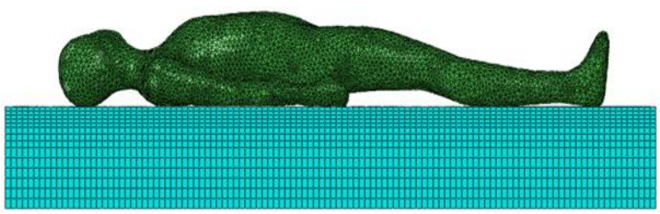

Figure 3. Finite element model of the supine position (side view).

For contact analysis: contact surfaces are defined between the human body and the mattress; the body surface (outer skin surface) and the top surface of the foam mattress are defined as master and slave surfaces, respectively. The under-surface of the mattress is fixed /12/. The coefficient of friction between the human model and the mattress is set to 0.4, /14, 16/.

The mesh of the mattress was graded from the top to the bottom. The type of mesh of the foam mattress is C3D8R.

Skin mesh is generated as a solid part with thickness of 2 mm of type C3D6. Mesh of muscle tissues is generated by four-node tetrahedron solid elements. Table 1 shows more details about the mesh property of the FEM model, /14, 17/.

RESULTS

Nine different compressive strengths of flexible polyurethane foam (FPF) are used to generate FE models to predict the contact pressure and displacement in our model of the foam mattress and human body of 63 kg weight in a supine position. We use half of the symmetry part for minimising computational cost. The skin is modelled as linear elastic material, the muscle and mattress foam are modelled as non-linear materials. The body force gravity is the main load in our model, and generated models do not contain a skeleton.

Nine kinds of varying degrees of mattress firmness and compressive strength are simulated to predict the parameters of comfort. Both contours of contact pressure and displacement are presented for nine foam compressive strengths. Figure 4 shows the variation in the body pressure distribution according to the firmness of mattress materials (FPF). The simulation predicted a contact pressure varied with the variation foam firmness, from 0.0167 MPa in the hard foam used, to 0.00448 MPa in the soft foam.

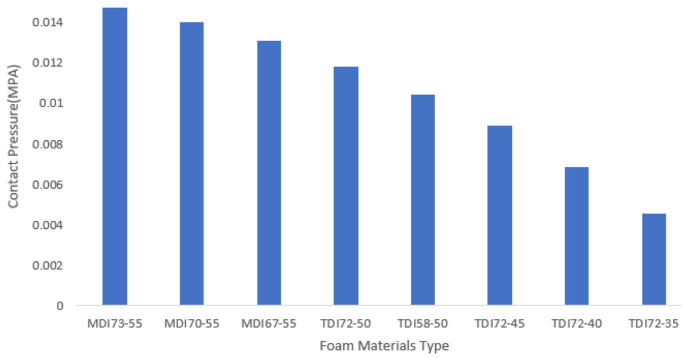

Figure 4. Contact pressure variation in MPa of foam materials (compressive strength).

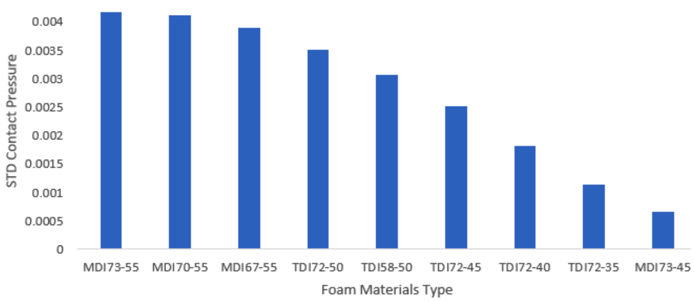

Figure 5. Standard deviation of contact pressure.

Figure 5 represents the variation of standard deviation to show the dispersion of contact pressure in the top surface of a different foam mattress. In this regard, the standard deviation of contact pressure decreases with a decrease of foam firmness, which means the good dispersion of contact pressure in the surface of the softer mattress. In Fig. 6 we represent the variation of displacement according to the variation of foam firmness. Displacement increases from 17.5 mm in the firm mattress foam to 213 mm in the soft mattress foam.

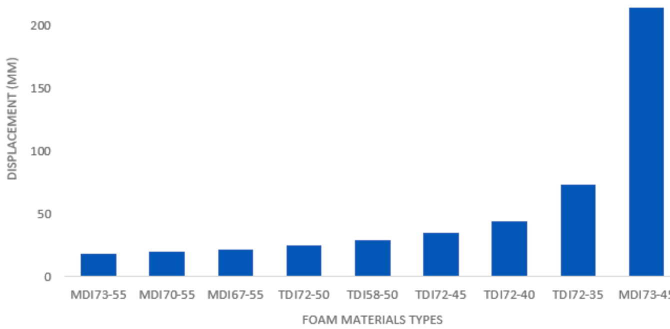

Figure 6. Displacement variation with compressive strength (mm).

Figures 7 and 8 show the contour of contact pressure and displacement, respectively, in the function of degrees of firmness (compressive strength). The peak of contact pressure and displacement are located in the buttock zone in all.

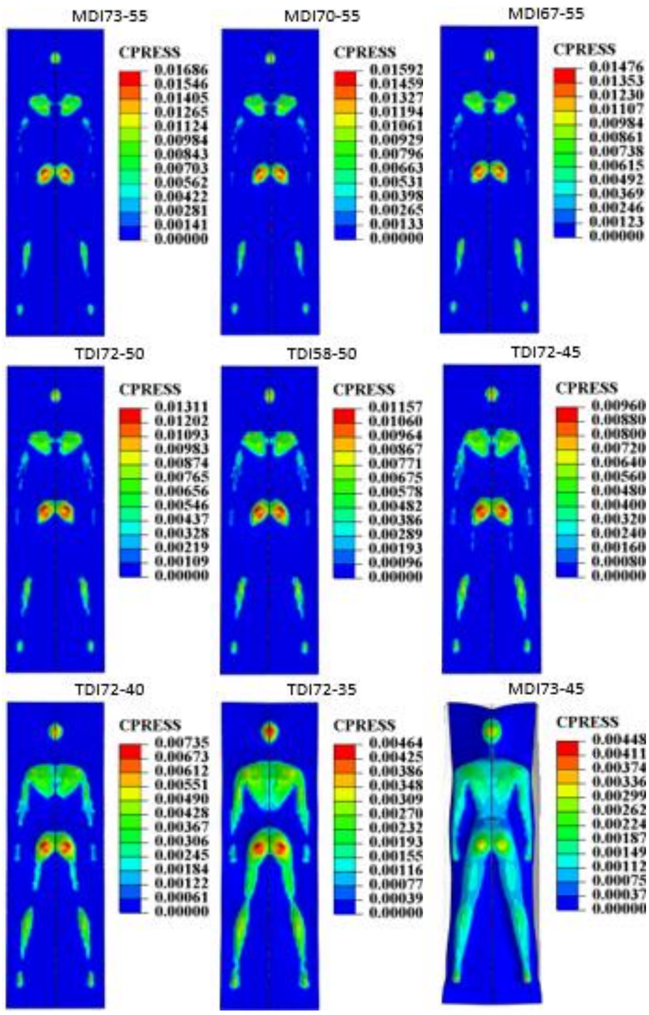

Figure 7. Contact pressure contours (MPa).

Difference of sinking displacement shows a linear change according to mattress firmness in the first seven firm foam mattresses, and the difference of sinking displacement increases when the mattress firmness decreases, and vice versa for contact pressure, when the mattress firmness decreases the contact pressure also decreases similarly with the dispersion of pressure in the top surface of the mattress.

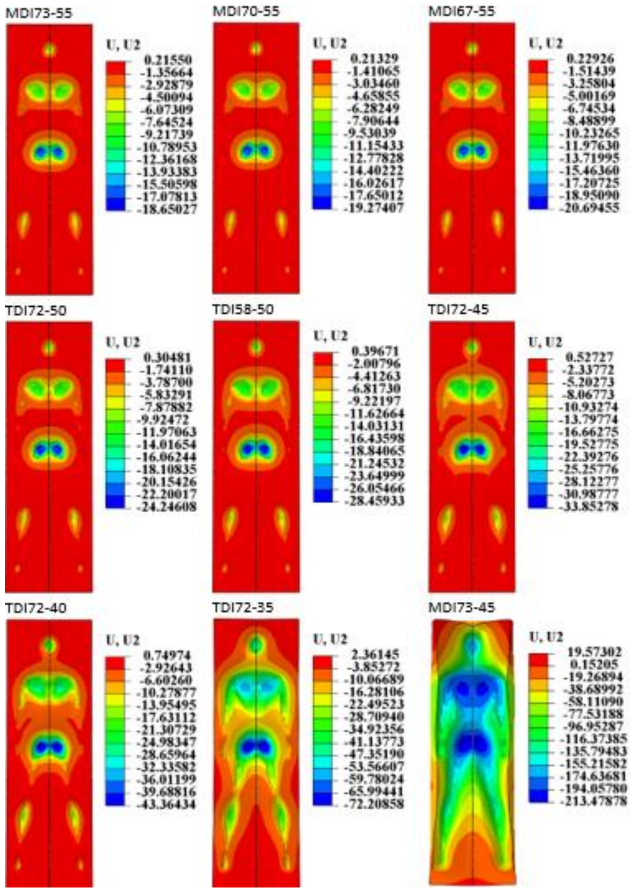

Figure 8. Displacement contours (mm).

Displacement of foam mattress and contact pressure, the two varied contraries to each other depend on the firmness of foam mattress. Soft foam divides the body force on a surface, allowing distribution of contact pressure on the surface and decreases its value. Firm foam gives more reaction force against the human body, prevents the sinking displacement in the mattress and increases contact pressure.

CONCLUSION

In this paper we generate a finite element model to predict basic parameters of foam mattress comfort. In comparison with the results of simulation data, and depending on the firmness of foam mattress, a higher level of contact pressure and low level of displacement is generated at the hard foam mattress, and the higher level of displacement in the gravity load direction and low level of contact pressure are generated in soft foam mattress, and we have good dispersion of contact pressure in soft foam mattress and bad dispersion of contact pressure in the hard foam mattress.

This study has several limitations. We developed a 3D FEM model of a human body lying on the mattress. Our model does not include a skeleton and does not include experimental validation of results. It is necessary to develop more human FEM models that reproduce various types of body forms.

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