ORIGINAL ARTICLE

Finite Element Estimation of Pressure Distribution inside the Trunk on a Mattress

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(**Received** 01 May 2015; **Accepted** 24 August 2015; **Published on line** 1 December 2015)

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DOI: 10.5875/ausmt.v5i4.949

Abstract: We developed a bedsore-prevention mattress and wheel chair cushion. Throughout development, we made numerous body pressure measurements on different mattresses and cushions. Such measurements required much time and effort. Simulation of body pressure has the potential to estimate the pressure distribution caused by physical parameters of different mattresses. In this study, we show attempts to model the body and estimate the pressure on its transverse plane. The computation was based on a non-linear finite element method with hyperelastic materials, such as muscle, skin and fat. Because the model simulates different tissues, we can estimate the pressure not only on the surface, but also that inside the trunk. The simulated results agreed well with actual pressure measurement results. Differences in physical properties of the mattresses were also modeled.

Keywords: Gerontechnology, finite element modeling, bedsore, mattress, elder care

Introduction

Pressure ulcers remain a common problem in rehabilitation care and gerontology. They are mainly caused by unrelieved pressure, friction, humidity, shearing forces, temperature, and under-nourishment, and restricted blood flow limits the reconstruction of skin tissue. Many patients suffering from paralysis due to brain infarctions have bedsores. Measures to address bedsores include reducing body pressure and decentralizing weight, reducing friction, improved ventilation, proper nutrition control, and the use of highly rebounding material to promote self-movement.

Numerical analyses of stress and strain conditions are now commonly used in product design, architecture, construction, and surgery. Most of these analyses use finite element methods. Haex (2005) analyzed the displacement of the spine and mattress in the side lying position, dividing the body model into head, shoulder, chest, pelvis, and feet. Stress and strain on the mattress are due to the weight of each body part, but the simulation did not consider soft tissues. THUMS, developed by Toyota's central R&D laboratory, is a virtual human body model that considers both bones and organs to simulate the physical impact of car collisions. Yoshida et al. (2008) developed a body model to research sleeping comfort. Bones, ligaments and intervertebral disks are assigned as linear elastic materials, and softer tissues, like fat and muscles, are considered hyperelastic materials. Interactions between the body and the mattress were analyzed in the sagittal plane.

We jointly developed a bedsore-preventing mattress with Panasonic and Toyobo Co. Ltd. Toyobo produces "Breathair," a material with excellent pressure diffusion and durability (Toyobo, 2008). It does not absorb water and can be dries quickly, making it potentially useful material for use in a bedsore-preventing mattress. The aim of development was to achieve better pressure dispersion than of urethane foam and provide more comfortable sleep. As a first step, we made measurements of body, pressure and deflection on 80 different Breathair samples.

The developed mattress has two layers: a softer fiber layer and a hard fiber layer of Breathair, to adapt to a large range of body weights. Its body pressure dispersion was better than that of urethane foam, and its subjective comfort evaluation was also the highest. The product, "Luckmat air," was launched in December 2008 by Panasonic and quickly became successful (Nagamachi et al, 2010, 2013, Ishihara et al., 2010).

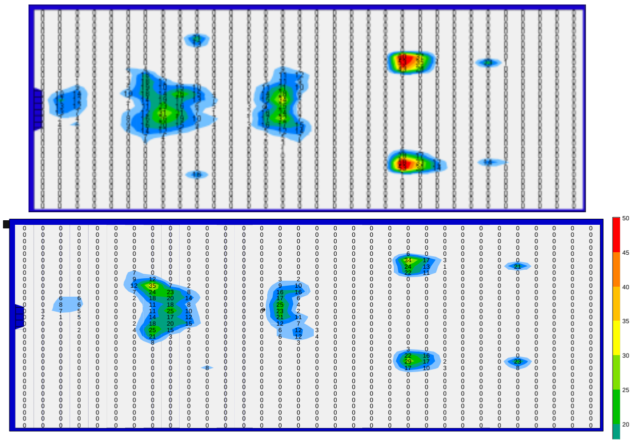

Figure 1. Body pressure distribution on high density urethane mattress (upper) and new mattress, Luckmat air (lower) (subject weight: 47kg).

Through this and other research on bed mattresses, we made many measurements of body pressure and deflections. Such measurements entail considerable effort and expense. Seven months of measurements were required for the development of the Luckmat air.

We considered the use of physical simulations because the stress and strain of the material are physical phenomena. Computer simulations could allow for variation of physical parameters, such as elasticity, without producing costly prototypes. Displacements and pressure distribution inside the body could also be modeled.

The purpose of this study was to develop a finite element model of the human body and confirm the results with actual pressure measurements. This will contribute to the effective development of future mattresses. Furthermore, it will provide simulation and visualization of strain inside the body and interactions with the mattress. First, we made a body trunk model and then performed simulations of displacement and stress. We then compared the simulation with pressure measurements on actual mattresses to validate the computer model.

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Simulation Methods

In this section, we describe modeling of the cross-section of the trunk, setting material constants and contact analysis.

Finite element model of human body

Body measurements of Japanese individuals were obtained from the AIST database (AIST, 1992). In this simulation, we used the bicrystal breadth, abdominal depth, shoulder breadth, and shoulder joint diameter. FEM modeling and computation were performed using ANSYS 12 (ANSYS Inc., www.ansys.com). We referred to anatomical and magnetic resonance imaging (MRI) images from the Visible Human Project (U.S. National Library of Medicine) to adjust the shape of the body cross-section.

Bicrystal breadth	272 mm
Abdominal extension depth	197 mm
Shoulder (bideltoid) breadth	456 mm
Scye depth	126 mm

Table 1. Japanese male body measures (mean), AIST database.

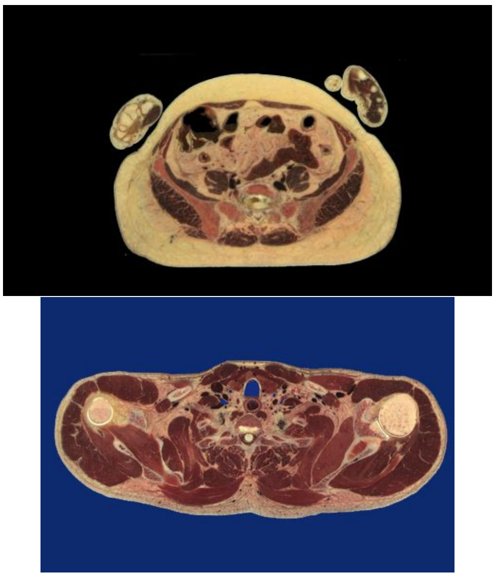

Figure 2. Cross-section of lumbar and shoulder from the Visible Human Project (http://www.nlm.nih.gov/research/visible/visible_human.html)

Our model includes seven substances: skin, subcutaneous fat, muscles, visceral fat, bones, esophagus, and trachea. Skin, fat and muscles are soft tissues and were modeled as non-linear hyperelastic materials using Ogden's formulation. Bones were modeled as linear elastic materials. The esophagus and trachea were modeled as linear elastic materials with limited intervals.

Non-linear hyperelastic materials are easily deformed by small forces, and the deformation is out of proportion to the force, like a soft gum. For example, the first force causes the first deformation. Then, a second force three times larger than the first may cause deformation less than three times that of the first force. A large force will cause plastic deformation without fracturing or breaking.

Material constants

Stress and strain analyses by FEM required material constants, Young's modulus and Poisson's ratio. Young's modulus indicates the stress and strain relationship. Poisson's ratio indicates the negative ratio of transverse to axial strain. When the material is incompressible (volume does not change) and deforms elastically, the Poisson's ratio becomes 0.5. If it is compressible (e.g., cork) and does not change its transverse size, the Poisson's ratio is near 0. Most solid materials have values between 0 and 0.5.

Material constants used in the analysis are shown in the Table 2. Parameters of human tissues were obtained from Linder-Ganz and Gefen (2004) and Yamamoto et al. (2008). Urethane foam parameters were obtained from the web page of Fuji Gomu ltd. (http://www.fujigomu.co.jp/simulation/urethan/).

We used Ogden's formulation for the hyperelastic materials' stress and strain model. Strain energy, *W*, is defined in Eq. (1). N is a positive constant. Each λ is the extension ratio in each axis, and α and μ are material parameters:

$$W = \sum_{i=1}^{N} \frac{\mu_i}{\alpha_i}\left(\lambda_1^{\alpha_i} + \lambda_2^{\alpha_i} + \lambda_3^{\alpha_i} - 3\right) \qquad (1)$$

Contact Analysis

We conducted a contact analysis between the mattress and trunk. To analyze stress and strain with the contact, we must first define the contact points and friction. Without setting touching points, the body slips slightly on the mattress when gravity is included in the model. Inside the body, bone, muscles and fat have unglued because each material has different deformations. We referred to the work of Prof. Klamecki of the University of Minnesota for setting contacts and the analysis (Klamecki, 2005).

Lumbar modeling

We constructed a two-dimensional cross-section (transverse section) lumbar model. The shapes and positions of tissues were derived from images of the Visible Human Project. The width of the bicrystal breadth was 272 mm, the Japanese male average. The trunk model and mattress are decomposed (meshed) with triangular elements. Five different materials were assigned: skin, fat, muscle, bone, and mattress. They are shown in different colors in Fig. 4. The mattress was 50 cm wide and 9 cm thick.

For contact analysis, contact points were defined between the trunk and the mattress. The friction coefficient was 0.5. The undersurface of the mattress was fixed. The stress and strain of the mattress, the lumbar region, and inside the lumbar region were computed. Every material in the simulation had its weight determined by the acceleration of gravity (9.8 m/s^2).

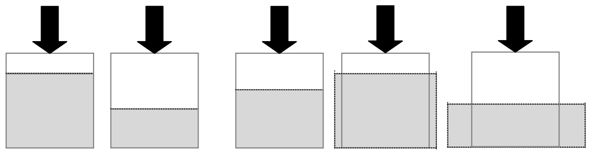

Figure 3. Deformations with various Young's moduli and Poisson's ratios. From left to right: Young's modulus, large and small; Poisson's ratio, 0.0, 0.3 and 0.5.

Hyperelastic materials	μ (MPa)	α	Density (kg/m^3)
Fat	0.010	30	1200
Muscle	0.003	5	1056
Skin	0.008	10	1056
Elastic materials	Young's modulus (MPa)	Poisson's Ratio	Density (kg/m^3)
Bone	$2{\times}10^4$	0.3	800
Esophagus and Trachea	0.047	0.49	1056
Urethane foam	0.025	0.0	48

Table 2. Hyperelastic and elastic material constants of the human body and mattress.

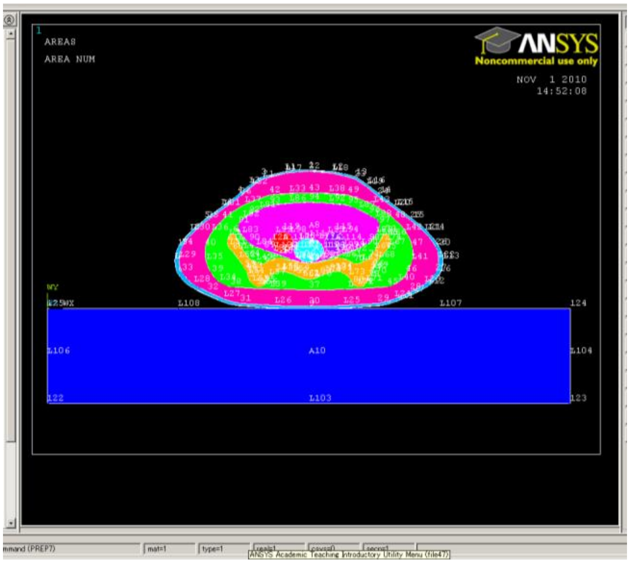

Figure 4. Lumbar model.

Upper shoulder modeling

The size of the shoulder model was also based on the average Japanese male. The shoulder breadth (bideltoid breath) was 456.2 mm and arm joint diameter (Scye depth) was 126.3 mm. This time, the mesh was tetragonal.

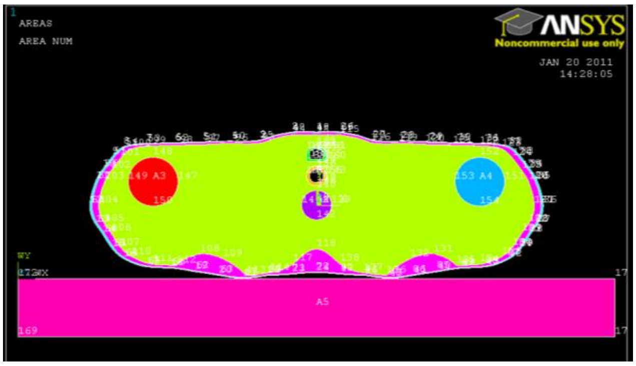

Figure 5. Shoulder model.

Results

Lumbar simulation

Simulating a 60-kg male body, the maximum stress on the skin was 5.19 kPa (39 mmHg), and stress on the subcutaneous fat was 2.53 kPa (19 mmHg) when lying down on the mattress, with a Young's modulus of 25 kPa. The mattress was slightly strained by the body weight.

Figure 7 shows the results of stress and deformation due to gravity. Deformation starts from both the body surface and the other side of the mattress. Then, stress and subsequent deformations propagate through the fat and muscles. Deformation propagates through the visceral fat and organs. Finally, the region below the pelvis and dorsal skin exhibits increased pressure, resulting in deformation and stress in the mattress.

Lumbar simulation: Comparison with actual pressure measurements

We compared the simulation results with actual measurements of body pressure. The pressure distribution was measured with the FSA system (Force Sensitive Applications, Canada). A commercial urethane foam mattress was used. The subject was a 73-year-old male weighing 63 kg. We asked the subject to lie down on the mattress and measured pressure on the mattress for 10 min. The subject was wearing a tracksuit bottom and a thin polo shirt. The average measured pressure around the sacrum was 4.27 kPa (32.03 mmHg). The simulated pressure of the corresponding area was 4.17 kPa (31.26 mmHg). The difference was small, so we considered the FEM simulation appropriate.

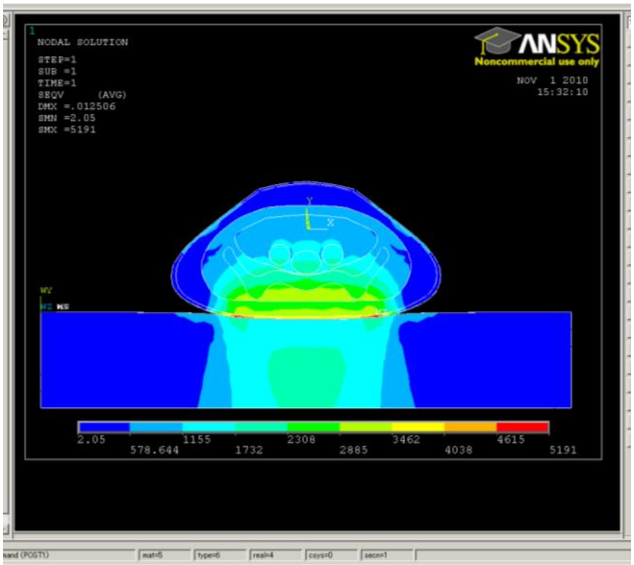

Figure 6. Computation result of lumbar model on a urethane foam mattress.

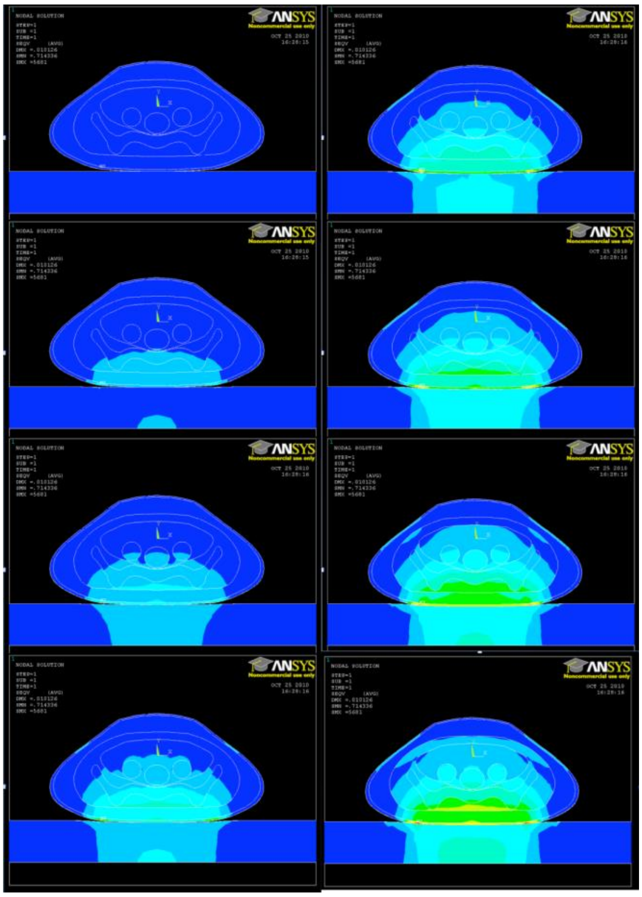

Figure 7. Animated results of stress and deformations by gravity: lumbar simulation.

Upper shoulder simulation: Comparison with actual pressure measurements

We used a 60-kg male body for the simulation, as in the lumbar simulation. The maximum pressure on the skin was 2.53 kPa (19.0 mmHg) and that on subcutaneous fat was 3.83 kPa (28.7 mmHg). The estimated pressure was lower than that for the lumbar region because the upper shoulder has large and thick muscles around the bones. The average measured pressure of the corresponding region was 1.32 kPa (9.87 mmHg), as shown in Fig. 7. The simulation result was 1.12 kpa (8.43 mmHg). The difference of 0.19 kPa (1.4 mmHg) was regarded as small.

Figure 10 shows the animated results. The upper shoulder has more muscles and less fat than the lumbar region, as shown in Fig. 2. Thus, stress and deformation quickly propagate to the front from the back. Because urethane foam has a very low Poisson's ratio, deformation inside the mattress is large in the vertical direction but small in the horizontal direction.

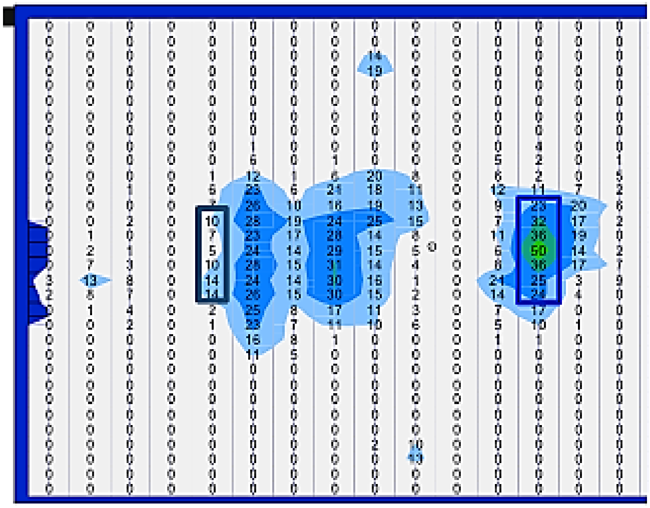

Figure 8. Actual pressure measurements on urethane foam mattress: shoulder (left box) and lumbar (right box).

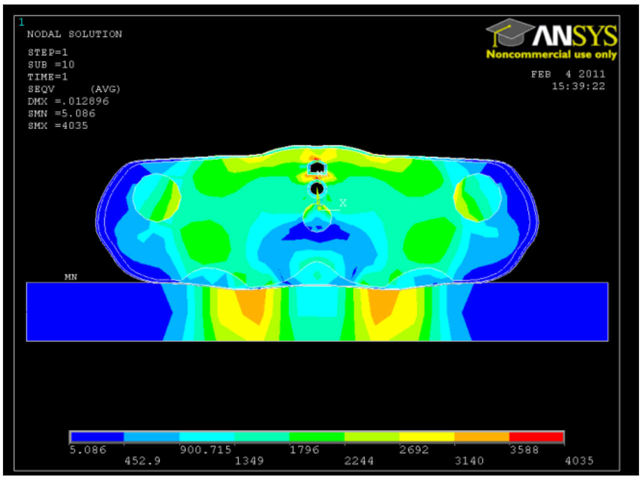

Figure 9. Computational results of upper shoulder model on urethane foam mattress.

Different mattress simulations

We also simulated two different commercially available steel spring mattresses. Both have different thin cushion layers (thin urethane foam layers, felt and non-woven cloth) below the surface and different types of springs. Young's moduli for the two different soft surface spring mattresses were measured. For mattress A, it was 0.016 MPa and for B, 0.004 MPa. The human body model was the same as that used in the upper shoulder simulations.

The main differences between the two simulations were the stresses on the front part and areas on the back of the shoulder. Mattress A, which was harder, had higher stress on the anterior part. Also, there were four high pressure points on the back. The softer mattress, B, had less stress on the front and two pressure points on the back. Most research focuses on back pressure but less on propagated stress of the front part . This finding would suggest further research is needed.

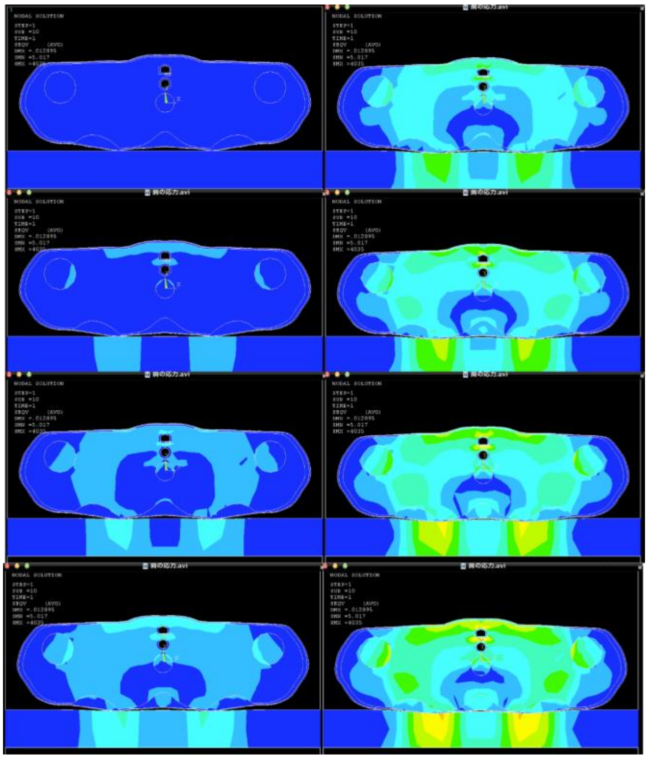

Figure 10. Animated results of stress and deformations by gravity: Upper shoulder.

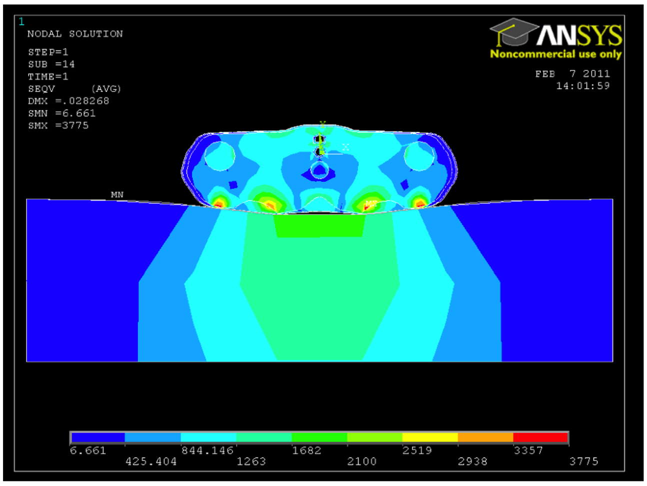

Figure 11. Simulation of spring mattress A.

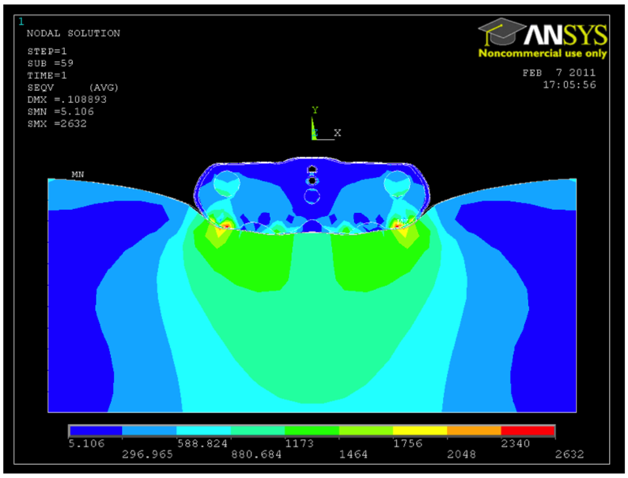

Figure 12. Simulation of spring mattress B.

Conclusion

We describe our attempts to model the body and estimate pressure on its transverse plane. Computations were based on a non-linear finite element method with hyperelastic materials, such as muscle, skin and fat. Because the model simulated different tissues, we could estimate the pressure not only on the surface, but also inside the trunk. The simulated results agreed well with actual pressure measurements.

Figure 13 summarizes the simulation process. Obtaining accurate anatomical shape and material constants is critical for determining simulation outcomes. Contact analysis is unique for this kind of hybrid material simulation. Non-linear FEM itself requires more extensive trials than conventional linear FEM, due to convergence difficulty. By collecting and integrating such simulation results, our model shows deep potential to assist non-experts of FEM like rehabilitation engineers and suppliers to propose optimal mattress designs.

Simulation Process Summary

1. Modeling anatomical structure

anatomical shape databases

2. Modeling mattress

material data

3. Applying material constants
Young's Moduli and Poisson's Ratios
of Elastic (Bone, Esophagus, Trachea and Urethane foam)
and Hyperelastic materials (Fat, Muscle, Skin).

4. Setting contact points (Contact analysis)
inside the body, between the body surface and mattress

5. Simulation
Non-Linear FEM

Figure 13. Simulation process summary

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