KEER2010, PARIS | MARCH 2-4 2010
INTERNATIONAL CONFERENCE ON KANSEI ENGINEERING AND EMOTION RESEARCH 2010

FINITE ELEMENT ANALYSIS TO INVESTIGATE SLEEPING COMFORT OF MATTRESS

Hiroaki YOSHIDA*, Masayoshi KAMIJO, and Yoshio SHIMIZU

Kansei Engineering Course, Division of Creative Engineering
Faculty of Textile Science and Technology, Shinshu University, Japan

ABSTRACT

There have been many studies to investigate the sleeping comfort of mattresses that have been evaluated sensory tests and body pressure distribution. Measurement of stress distribution within the human body would provide valuable information. Numerical analysis is one of the most desirable techniques to estimate stress distribution in lieu of an invasive measurement. In this study, a two-dimensional human body-mattress model was developed by using Finite Element method to examine sleeping comfort of mattress.

We constructed both male and female Finite Element models with the use of the statistical data on Japanese human body dimensions. We utilized von Mises stress as an evaluation criterion of sleeping comfort and performed the Finite Element analysis iteratively while modifying Young's moduli of mattress to investigate which mattress firmness yields the lowest stress on the lumbar region.

When Young's modulus of mattress was of medium firmness (that is, neither high nor low), the lowest stress on the lumbar region was found and sleeping comfort was regarded to be most appropriate. As a result of the Finite Element analysis, this characteristic of mattress firmness generated the lowest stress within the human body was changed owing to the difference of both human body dimensions and material properties of the human soft tissues. Subjective preference of mattress firmness is assumed to be determined according to body dimensions and material properties of the human soft tissues. Therefore, Finite Element analysis is considered to be one of the best tools for studying the sleeping comfort of mattresses.

Keywords: *Finite Element analysis, Sleeping comfort, Human body dimensions, Mattress*

---

* **Corresponding author**: 3-15-1 Tokida, Ueda 386-8567 Japan, e-mail: hyoshida@shinshu-u.ac.jp

1. INTRODUCTION

Most people spend around one third of their life sleeping, and so the ability to obtain a comfortable sleeping experience is very important. Sleeping comfort is affected by multiple factors and mattress quality is considered one of the most essential elements because the mattress directly contacts the human body. There are many studies to investigate sleeping comfort of mattress that has been evaluated using sensory tests and body pressure distribution [3] [4] [5] [6] [8]. Measurement of stress distribution within the human body would provide valuable information, however, this measurement involves invasive testing procedures, not to mention the "stress" on the subject is severe. Therefore, numerical analysis is considered to be one of the most desirable techniques to estimate stress distribution within the human body in lieu of an invasive measurement approach. [7] [8] [9].

In this study, in order to examine sleeping comfort of mattress, a two-dimensional human body-mattress model was developed using the Finite Element method. From the viewpoint of stress analysis, we investigated the relationship between human factors (human body dimensions and material properties of the human body) and various mattress types, especially focusing on mattress firmness.

2. METHODS

We constructed two-dimensional Finite Element models, based on the X-ray photogram of a male adult (Fig 1 and Fig 2) [7] [9]. Two models, one male and the other female, were modified using the statistical data on the human body dimensions of average Japanese adults. This statistical dataset was created by AIST (The National Institute of Advanced Industrial Science and Technology, Japan) in 1991 and 1992 [1].

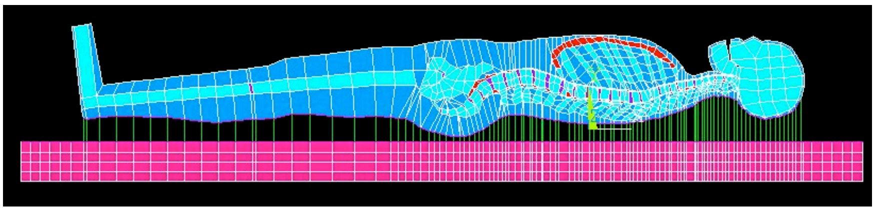

Figure 1: Two-dimensional male Finite Element model

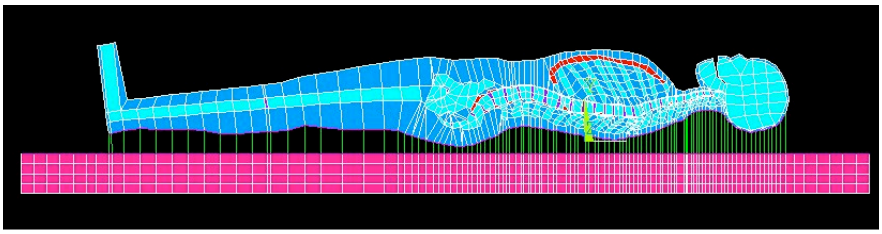

Figure 2: Two-dimensional female Finite Element model

Ten body dimensions (Height, median chest depth, waist depth, abdominal depth, abdominal extension depth, buttock depth, thigh depth, knee depth, maximum lower leg depth, and minimum lower leg depth) [1] were utilized in this study and the characteristics of the human depths were used to create our Finite Element models. The features of the human body dimensions are as follows; the average height is 171cm for the male model and 160cm for female model. The thigh depth for female model is thicker than that of male model. In the remaining nine body dimensions, for male model dimensions were larger than those of female model.

Each human model consists of bones, ligaments, intervertebral discs, and the human soft tissues because human skin and muscles etc. were hypothesized to be a one-layered structure of soft tissues. Both models contained the same 800 elements. A mattress model was treated as a homogeneous one-layered structure.

We created nodes of the human models that corresponded to the measurement points of human body dimensions and established other nodes of outer layer (surface nodes of the human soft tissues) that connected former nodes manually and smoothly. Internal nodes (nodes of bones etc.) were prepared based on data from X-ray images.

Bones, ligaments, and intervertebral discs of the human models were assumed to be linear elastic and material properties of each component were obtained from the literature (Table 1) [7].

Table 1: Material properties

	Young's modulus (MPa)	Poison's ratio
Bone	10,000	0.3
Ligament	5	0.3
Disc	1	0.49

The human soft tissues and mattress were presumed to be hyperelastic because the dominant nonlinear elastic property was hypothesized to be hyperelastic [9]. We employed a Neo-hookean form as the hyperelastic model. The form of the Neo-hookean strain energy potential W is

$$W = \frac{G_0}{2}(\overline{I_1} - 3) + \frac{K_0}{2}(J - 1)^2 \qquad (1)$$

where G_0 is the initial shear modulus, K_0 is the initial bulk modulus, $\overline{I_1}$ is the first deviatoric strain invariant, and J is the elastic volume ratio [2]. The initial shear modulus and the initial bulk modulus were calculated from Young's modulus E and Poison's ratio ν using equation (2) as below. Poison's ratio was set up as 0.49 for soft tissues and 0.01 for mattress in this study.

$$G = \frac{E}{2(1+\nu)} \qquad K = \frac{E}{3(1-2\nu)} \qquad (2)$$

The density of all elements of the human models was assumed to be 1000kg/m3 and body weights were set at 62kg for the male model and 53kg for the female model by establishing the thicknesses of two human models (23cm for the male model and 22cm for the female model, respectively).

In order to simulate a sleeping state lying on mattress, contact elements were incorporated between the human body and the mattress, with the coefficient of friction was set at 0.5. Gravity was applied to the human model and the bottom nodes of the mattress were fixed in all directions.

We utilized von Mises stress within the human body as an evaluation criterion of sleeping comfort. If the stress distribution of a node in the lumbar region is low, the sleeping comfort is hypothesized to be appropriate. In order to determine the mattress firmness which yields the lowest stress of the human soft tissues on the lumbar region, we performed the Finite Element analysis iteratively while changing Young's moduli of mattress after Young's moduli of the human soft tissues were prepared from 0.1MPa to 1.0MPa. A Finite Element analysis package ANSYS Ver.10 (CYBERNET SYSTEMS CO., LTD., Japan) was used in this study.

3. RESULTS

Figures 3 and 4 are analytical results of the stress distribution of the male model when Young's modulus of the human soft tissues was defined as 0.5MPa, and Young's modulus of mattress is 0.003MPa for Figure 3 and 0.02MPa for Figure 4, respectively. It was observed that not only deformation of mattress but also stress distribution within the human model was different according to the change in mattress firmness.

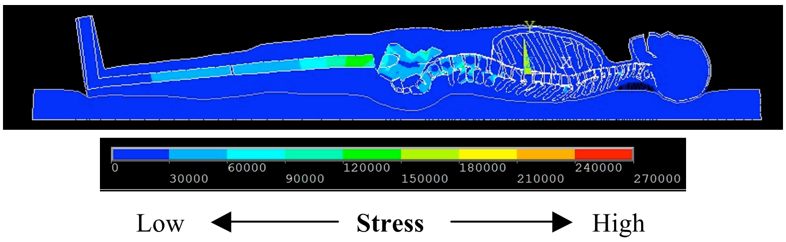

Figure 3: Result of stress distribution when Young's modulus of mattress was 0.003MPa

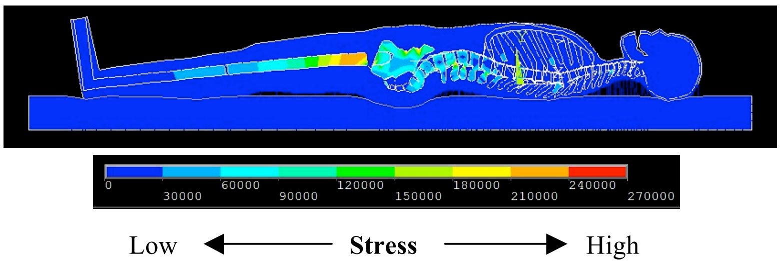

Figure 4: Result of stress distribution when Young's modulus of mattress was 0.02MPa

Although Young's moduli of the human soft tissues were the same among the male model and the female model, von Mises stress of the male model was higher than that of the female model (Fig 5).

When Young's moduli were comparatively higher (firmer mattress) or lower (softer mattress), von Mises stresses in the lumbar region was larger. However, when Young's modulus of mattress was neither high nor low (medium-firm mattress), the lowest stress on the lumbar region was found (Fig 5).

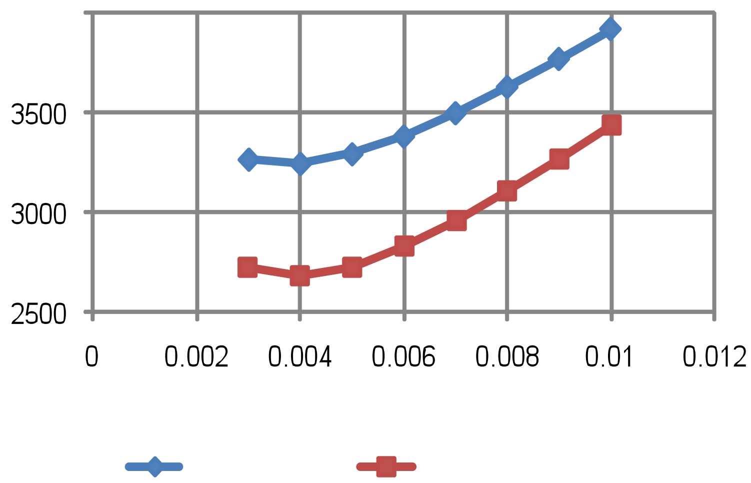

Figure 5: von Mises stress in the lumbar region of male model and female model while Young's moduli of mattress changed

As a result of the iterative Finite Element analysis, the characteristic of mattress firmness generated the lowest stress within the human body was changed according to the difference of material properties of the human soft tissues (Fig 6).

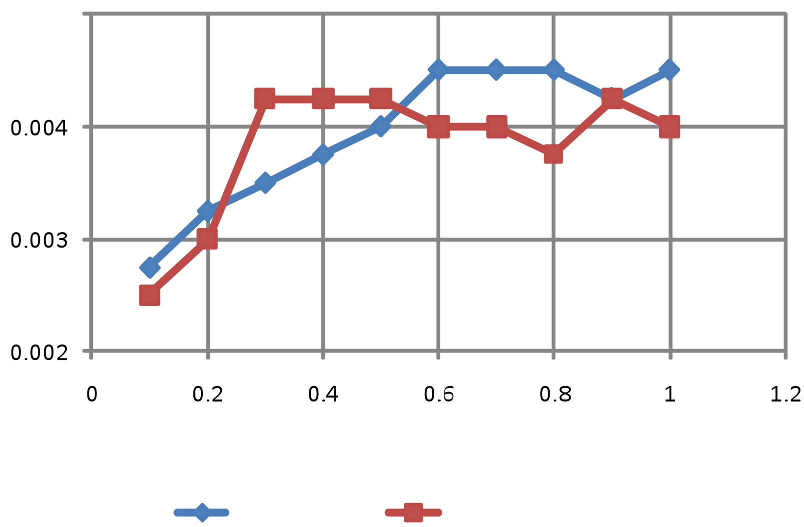

Figure 6: Result of the iterative analysis to investigate Young's moduli (mattress firmness) that yields the lowest stress of the human soft tissues while modifying Young's moduli of mattress after Young's moduli of soft tissues were set from 0.1MPa to 1.0MPa.

4. DISCUSSION

In this study, we developed two-dimensional Finite Element models. The human body and a mattress have three-dimensional structures and consideration of this nature is required in order to research sleeping comfort accurately. However, it is both problematic and time consuming to construct a three-dimensional model. If we attempt to understand sleeping comfort qualitatively, it is not necessary to examine a three-dimensional condition. Rather, it is sufficient to employ a two-dimensional model and it is possible to prepare a Finite Element model that represents a subject's characteristics of human body dimensions in a simpler manner, which corresponds to individual feature of body type readily. Therefore, we utilized two-dimensional models in this study.

As shown in Figure 5, von Mises stress of the male model was higher than that of the female model although Young's moduli of soft tissues were the same. This result stems from the difference of human body dimensions because several body dimensions of the male model are larger than those of the female model. Yamazaki et al. reported that subjective preference of bed cushion's properties was different between obese type and thin type and this research is associated with our result [8]. Bader et al. also mentioned that body size can affect sleep [3]. Therefore, variation of individual human body dimensions is supposed to differentiate subject preference of mattress firmness.

When Young's moduli were comparatively higher (firmer mattress) or lower (softer mattress), von Mises stresses was larger, however, when Young's modulus of mattress was neither high nor low (medium-firm mattress), the lowest stress was found and sleeping comfort is regarded to be most suitable (Fig 5). Kovacs et al. found that a mattress of medium firmness improves pain among patients with low back pain [5] and this literature supports our result. Why is medium-firmness mattress preferable? We consider that there are some reasons and one of the most important is sleep posture [8]. When lying on softer mattress, since the pelvis falls into the mattress and the buttock region is pressed by mattress, there is a possibility that a subject feels uncomfortable. When lying on harder mattress, a subject could feel sore because the contact area between the human body and mattress decreases and concentration of pressure will occur around the back. On the other hand, when lying on medium-firm mattress, the contact area and a fall displacement of the human body into mattress are assumed to be appropriate and sleeping comfort is perceived to be the most suitable.

As a result of the iterative Finite Element analysis in Figure 6, the characteristic of mattress firmness generated the lowest stress was changed owing to the difference in material properties of soft tissues. If material properties of the human soft tissues are relatively low (that is, a person has a softer skin), sleeping comfort could increase when lying on softer mattress. Material properties of the human soft tissues is one of the important factors that affects sleeping comfort and it is assumed that subject preference is influenced by material properties of the human soft tissues.

Based on results in Figures 5 and 6, it is assumed that subjective preference of mattress firmness is determined according to human body dimensions and material properties of the human soft tissues. Since we developed the human models based on the average body dimensions, we should construct several body types of Finite Element human models (obese type, thin type and so on) in order to investigate appropriate mattress firmness rigorously.

There are some limitations in this study. Although we performed a parametric study to investigate mattress firmness that yielded the lowest stress, we tentatively input the material properties of the human soft tissues. It is necessary to measure the real material properties of soft tissues and to utilize this data for Finite Element analysis in future studies. Finite Element models of the human body is one-layered structure as soft tissues, however, soft tissues consist of the epidermis, subcutaneous tissues, and muscles. Therefore, it is essential to develop a human model that structures the multiple layers accurately.

There are few studies about sleeping comfort by using a numerical method [8] [9]. If a numerical technique enables us to demonstrate internal state of the human body and to investigate a sleeping state, it facilitates evaluation of not only sleeping comfort but also product design of mattress. In this study, two-dimensional human body-mattress models were developed using the Finite Element method and it was possible to simulate deformation of mattress and stress distribution within the human body. This study is a preliminary approach and if the human model can be constructed more precisely in the future, the Finite Element analysis is considered to be one of the desirable tools to study sleeping comfort of mattress.

5. SUMMARY

We constructed a male and a female Finite Element models to simulate the sleeping state lying on mattress. In order to investigate which mattress firmness yields the lowest stress in the lumbar region, we performed the Finite Element analysis iteratively while modifying Young's moduli of mattress.

When Young's modulus of mattress was of medium firmness (neither high nor low) , the lowest stress in the lumbar region was found and sleeping comfort was regarded to be the most appropriate. As the result of the Finite Element analysis, the characteristic of mattress firmness generated the lowest stress within the human body was changed owing to difference of both human body dimensions and material properties of the human soft tissues. Subjective preference of mattress firmness is assumed to be determined according to body dimensions and material properties of the human soft tissues. The Finite Element analysis is considered to be one of the best tools to examine the sleeping comfort of mattresses.

REFERENCES

[1] AIST Human Dimensions Data 1991-1992, <http://riodb.ibase.aist.go.jp/dhbodydb/>

[2] ANSYS Theory Reference

[3] Bader G., and Engdal S., The influence of bed firmness on sleep quality, *Applied Ergonomics*, Vol. 31, pp.487-497, 2000.

[4] DeVocht J., Wilder D., Bandstra E., and Spratt K., Biomechanical evaluation of four different mattresses, *Applied Ergonomics*, Vol.37, pp297-304, 2006.

[5] Kovacs F., Abraira V., Peña A., Martín-Rodríguez J., Sánchez-Vera M., Ferrer E., Ruano D., Guillén P., Gestoso M., Muriel A., Zamora J., Gil del Real M., and Mufraggi N., Effect of firmness of mattress on chronic non-specific low-back pain: randomised, double-blind, controlled, multicentre trial, *The Lancet*, Vol. 362, pp.1599-1604, 2003.

[6] López-Torres M., Porcar R., Solaz J., and Romero T., Objective firmness, average pressure and subjective perception in mattresses for the elderly, *Applied Ergonomics*, Vol.39, pp.123-130, 2008.

[7] Uenishi K., Tanaka M., Yoshida H., Tsutsumi S., and Miyamoto N., Driver's fatigue evaluation during long term driving for automotive seat development, *Society of Automotive Engineers (SAE)*, No.2002-01-0773, (SP-1670, Human Factors in Seating and Automotive telematics), pp.71-77, 2002.

[8] Yamazaki N., Satoh S., and Tachikawa R., Biomechanical Fitting of Bed Mattresses [in Japanese], *Society of Biomechanisms*, Vol. 12, pp.61-71, 1994.

[9] Yoshida H., Kaneshige K., Kamijo M., and Shimizu Y., Finite Element analysis to investigate sleeping comfort based on human body dimensions [in Japanese], *In the proceeding of the 10th Annual Conference of JSKE (Japan Society of Kansei Engineering) 2008*, Tokyo, 2008.