10

Analysis of human pressure ulcer and cushion pads for its prevention

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1. Introduction

Pressure sore ulcers can be a serious problem for bedridden patients. The first indication of ulcer formation is redness on the skin surface. However, some practitioners have found evidence that ulcers form in deeper tissue and then spread toward the surface of the skin (Daniel et al., 1982; Koshimura et al., 2004). By the time surface damage is noticed, subcutaneous fat tissue necrosis has already occurred (Fig. 1). It sometimes manifests as an undermining formation (Fig. 2) and it tends to extend.

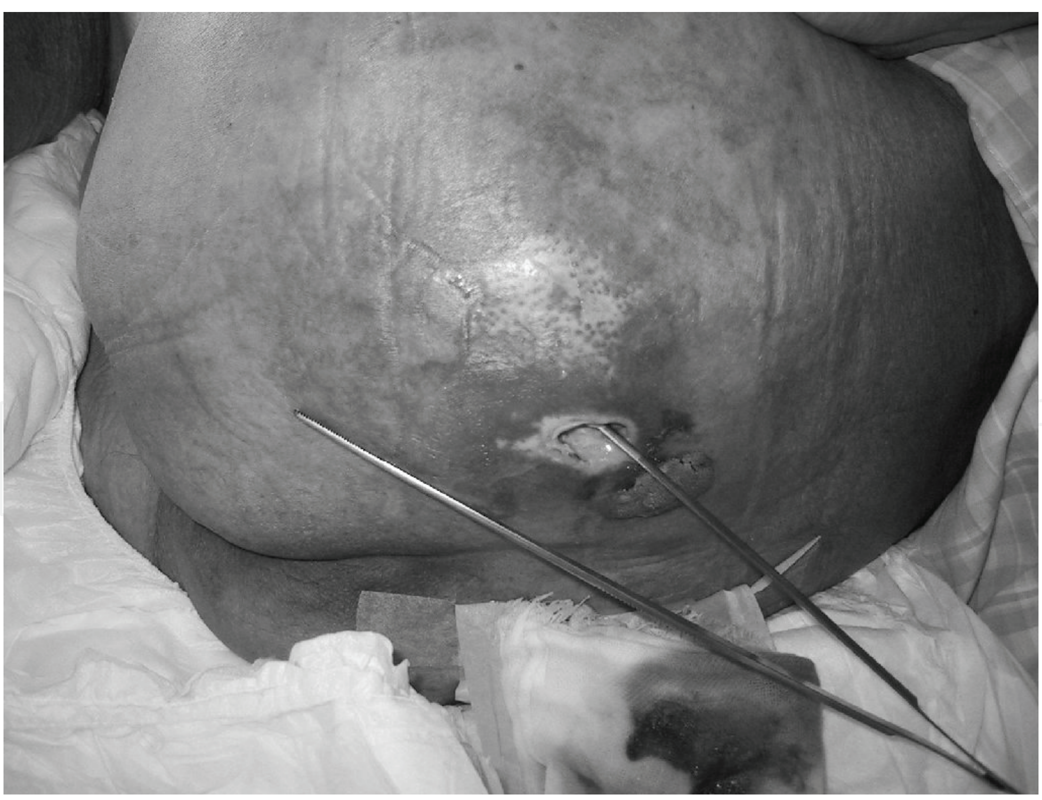

Fig. 1. Pressure ulcer with undermining: Pressure ulcer sometimes found with deeper tissue necrosis.

There have been several studies of finite element analysis (FEA) of pressure ulcers (Chow & Odell, 1978; Mak et al., 1994; Honma & Takahasi, 2001; Ragan et al., 2002). Todd and Thacker demonstrated the consistency of the finite element model in analysis of pressure ulcers (Todd & Thacker, 1994).

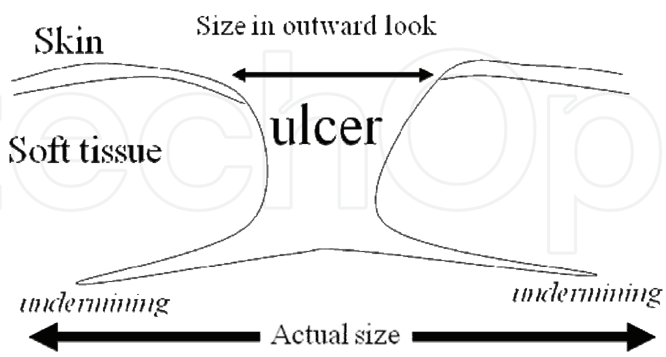

Fig. 2. Pressure ulcer with undermining: Cross sectional schematic of a pressure ulcer. Pressure ulcers are sometimes found with deeper tissue necrosis.

The author hypothesized that structural change (i.e. undermining formation) causes worsening of stress distribution of the wound. The finite element model can be used to characterize the extension mechanism of pressure sore with undermining.

In this chapter, author show some studies to analyze stress distribution that affect damage of soft tissue that is emergence of pressure ulcers. In the first study (Study 1), analysis in different sized undermining with vertical directional load was done.

In actual bedridden patients, load is not only gravity. They are pushed and rotated by nursing staffs. In the second study (study 2), the author added analyses for different directional load that will occur in actual situation.

Thick cushion pads are sometimes used for prevention of pressure ulcers. A thick cushion pad is useful for reduction of stress concentration caused by a vertical directional load. The author hypothesized that even if a cushion pad was vertically thin, it would effectively reduce oblique loads, which can increase stress concentration.

The third study was to analyze the stress distribution of a model of the human body attached to a thin cushion pad with a range of hardness, to assess the effectiveness of the cushion pad in reducing stress concentration.

The purpose of these studies were to describe the stress distribution of pressure ulcers in combination of various geometric and load conditions. The present findings support a hypothesis that after a small necrosis arises in a deep region of the body, it induces structural change that results in a structure that facilitates mechanical extension mechanically of the necrosis(Kuroda & Akimoto, 2005; Akimoto et al., 2007).

All data analysis was performed using a personal computer (Pentium 4: 2.4 GHz with 1 GB RAM) and ADINA analytical software (version 8.3, ADINA R&D, Inc., Massachusetts, U.S.A.)

2. Materials and methods (Study 1)

The first assumption of the model was that the shape of the human trunk is a cylinder. The second assumption was that the human body consists of 2 categories of tissue: soft tissue and hard tissue. Soft tissue corresponds to structures such as skin, fat and muscle. Hard tissue corresponds to bone. To simplify the calculations, only the lower half of the cylinder model was used. Thus, the cross section of the basic model consists of 2 concentric semicircles. The outer semicircle functions as the soft tissue, and the inner semicircle functions as the hard tissue (Fig. 3).

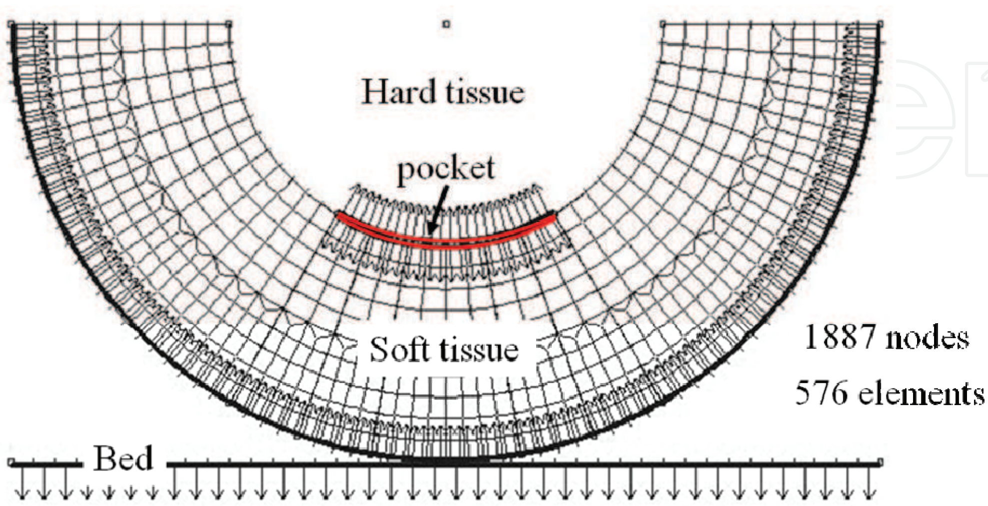

Fig. 3. Basic design of pressure sore model: A hollow half cylinder with a diameter of 20 cm was used to represent the soft tissue. A cylinder with a diameter of 10 cm was used to represent the hard tissue. Undermining was represented by a small gap at the junction of the soft and hard tissue. Model was meshed into 1887 nodes and 576 elements.

For FEA, the soft tissue and the cushion pad were combined into a mesh with a basic geometry of 1887 nodes and 576 elements.
Assuming the simplest clinical state, the following basic parameters of FEA were assigned values: geometry, material properties, loading condition and boundary condition. Analysis was performed in 2 dimensions.
Geometry:
A hollow half cylinder with a diameter of 20 cm was used to represent the soft tissue. A hollow half cylinder with a diameter of 10 cm was used to represent the hard tissue. Undermining was represented by a small gap at the junction of the soft and hard tissue. The upper and lower edges of the undermining were designed so that they comprised a contact pair with no friction. For evaluation, four different models were prepared:

1) no undermining (no gap);
2) small undermining (gap, 1.7 cm);
3) medium undermining (gap, 3.5 cm); and
4) large undermining (gap, 5.2 cm)

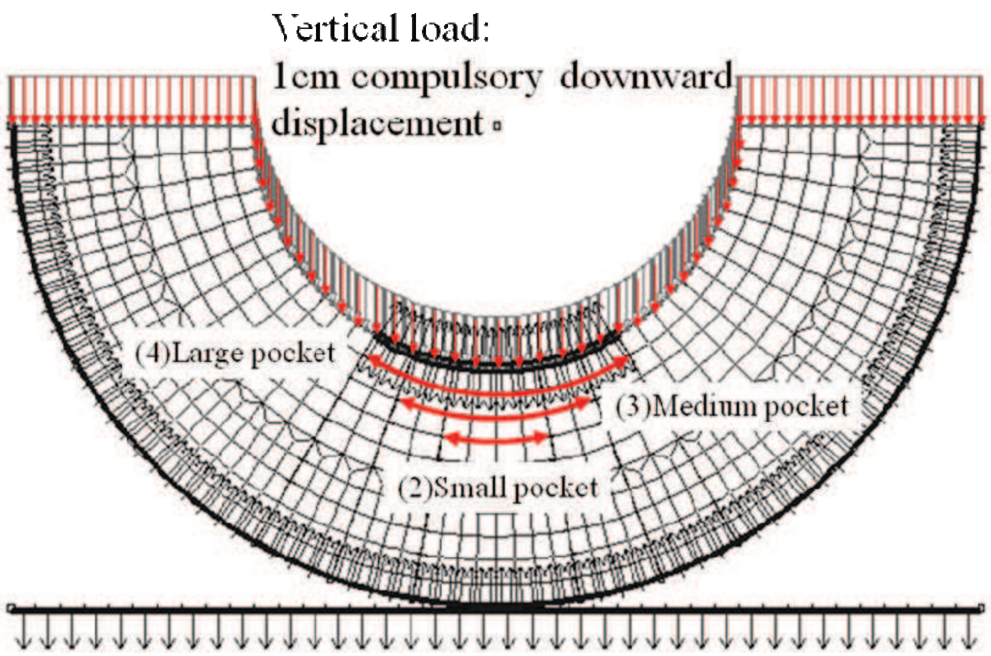

Fig. 4. Undermining size and load condition for study 1: Four different sized models were prepared: 1) No undermining (no gap); 2) Small (gap, 1.7 cm); 3) Medium (gap, 3.5 cm); and 4) Large undermining (gap, 5.2 cm). A 1-cm downward displacement on upper edges to represent gravity.

Material Properties:
Actual biological tissue is nonlinear, anisotropic and visco-elastic. To simplify the calculations, the specific microstructure of the tissue was not taken into account. It was assumed that the soft tissue was linear, isotropic, and time-independent. Young's module of the soft tissue was set to 15 kPa. Poisson's ratio of the soft tissue was set to 0.49.

Loading Conditions:
Vertically directed loading was included to represent gravity. This loading is expressed as a 1 cm downward displacement of the upper edges of the model.

Boundary Conditions:
The patient was assumed to be lying on a flat, hard, non-slip bed. For this purpose, a tangential line was drawn adjacent to the lower edge of the soft tissue. This line was fixed in all directions, and formed a contact pair with the edge of the soft tissue or the edge of the cushion pad. The coefficient of friction was set to 1.0 for these contact pairs.

3. Results (Study 1)

Results of the FEA were summarized and visualized using a von-Mises stress distribution map. On the stress distribution map of the model with no undermining, a large concentration of effective stress was observed at the centre just under the hard tissue, and also at the junction of soft and hard tissue. In both regions, the amount of effective stress was approximately 4.0 k Pa (Fig. 5).

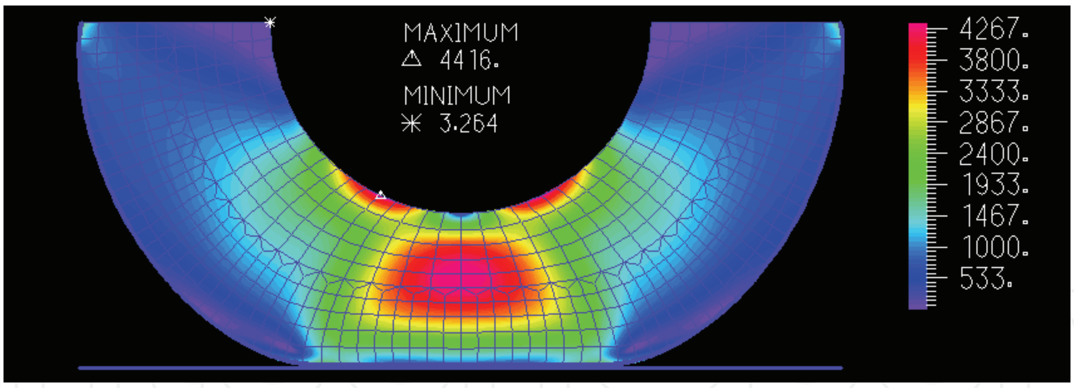

Fig. 5. Stress distribution of no-undermining model

The model with a small undermining had nearly the same pattern of stress distribution as the model with no undermining. Also, the maximum amount of effective stress was the same as that of the model with no undermining (Fig. 6).

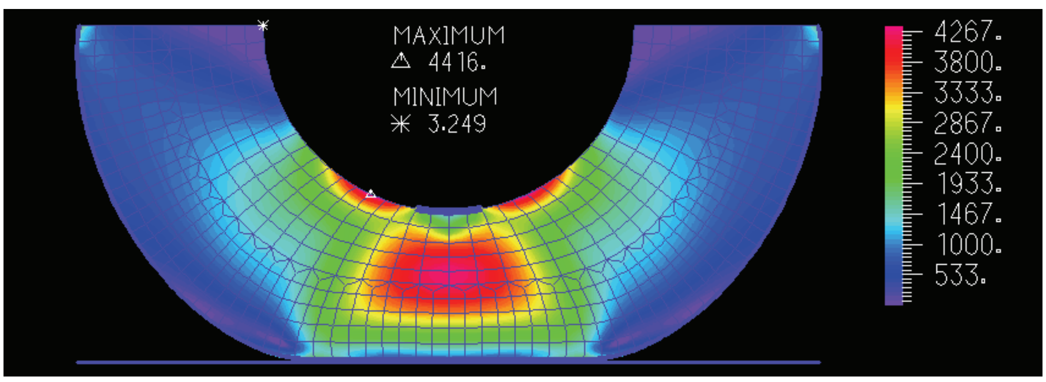

Fig. 6. Stress distribution of small undermining model

In the model with medium undermining, the points of maximum effective stress were at the edge of the undermining. The maximum amount of effective stress was 6168 Pa. Stress was also concentrated immediately under the hard tissue, with a local maximum amount of effective stress of about 4.0 k Pa (Fig. 7).

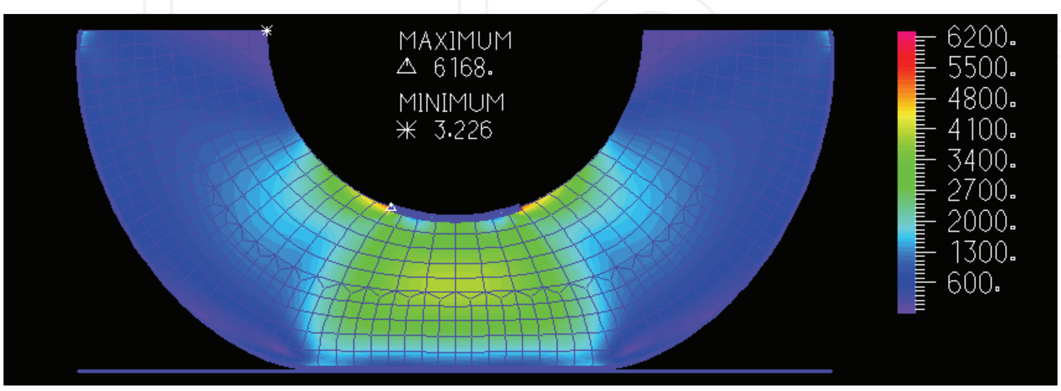

Fig. 7. Stress distribution of medium undermining model

In the model with large undermining, the points of maximum effective stress were at the edge of the undermining. The maximum amount of effective stress was 7.7 k Pa. Stress was also concentrated under the hard tissue, with a local maximum amount of effective stress of about 4.0 k Pa (Fig. 8).

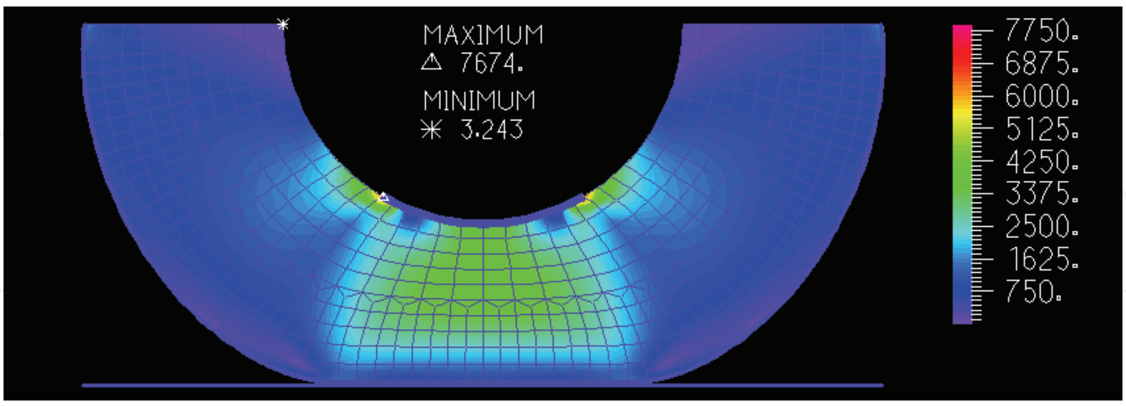

Fig. 8. stress distribution of large undermining model

A series of examinations revealed two main areas of stress concentration:
1) At the junction of hard and soft tissues, or the edge of the undermining
2) The centre of the soft tissue just under the hard tissue.
The maximum amount of effective stress increased with increasing size of undermining (Fig. 9).

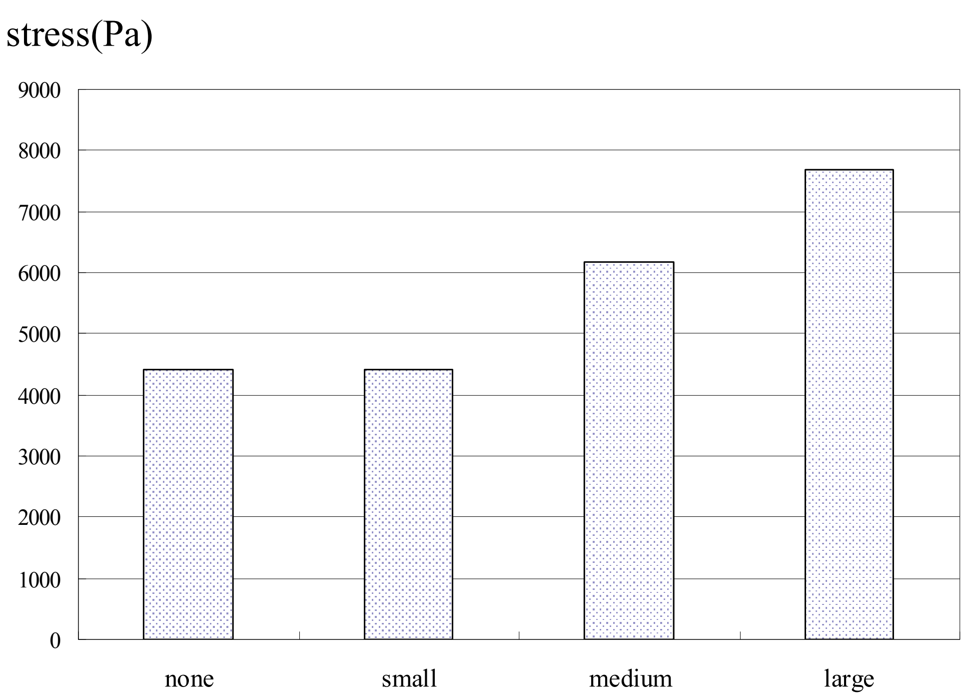

Fig. 9. Maximum effective stress (Study 1): Amount of maximum effective stress increased with increment of undermining size

4. Materials and methods (Study 2)

Basic geometry, material properties and boundary conditions were the same as those of the study 1.
Under actual clinical conditions, patients do not generally remain in the same position at all times. They are moved or rotated during nursing care. To simulate these conditions, the model was subjected to horizontal displacement. The model conditions included 1 cm of horizontal movement and 1 cm of vertical movement, representing horizontal and vertical displacement resulting from horizontal and vertical loads, respectively (Fig. 10).

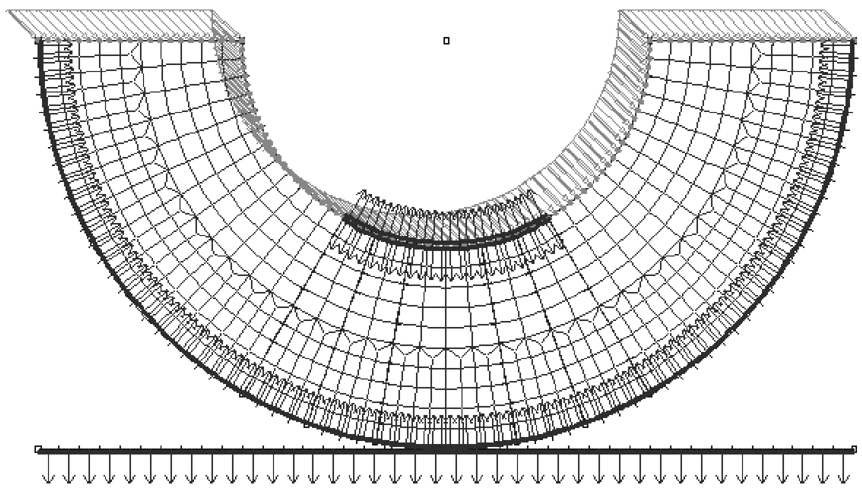

Fig. 10. Model and loading conditions for study 2

5. Results (Study 2)

Results of the FEA were summarized and visualized using a von-Mises stress distribution map. In a condition with additional 0.33 cm horizontal load, distribution of stress had changed. Larger stress concentration emerged at the edge of the undermining in each size of undermining. In a condition with additional 0.66 cm horizontal load, distribution of stress pattern showed more biased stress concentration. The amount of effective stress was increased. Further increment of stress was observed in each undermining patterns of 1.0 cm horizontal load model (Fig. 11-13).

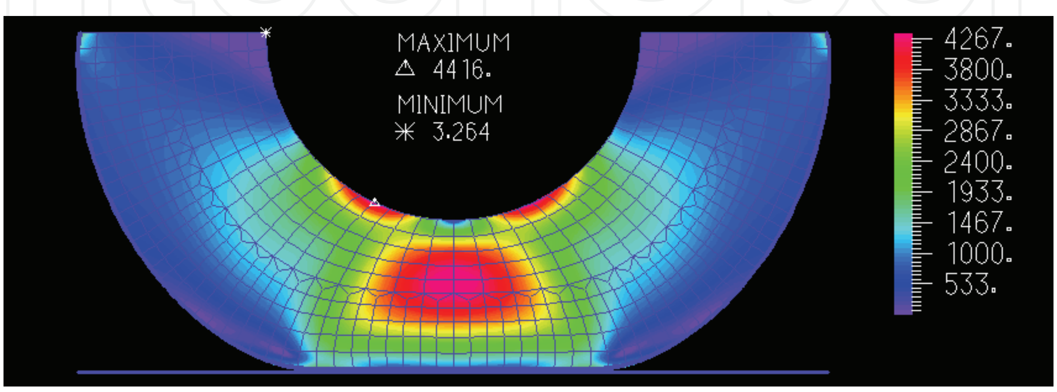

Fig. 11. Stress distribution in no gap model with a straight load

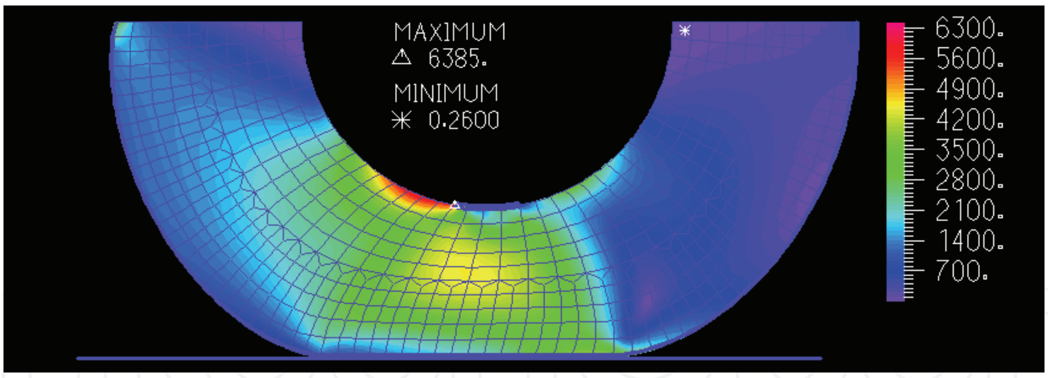

Fig. 12. Stress distribution in small gap model with an oblique load (1.0 cm horizontal + 1.0 cm vertical)

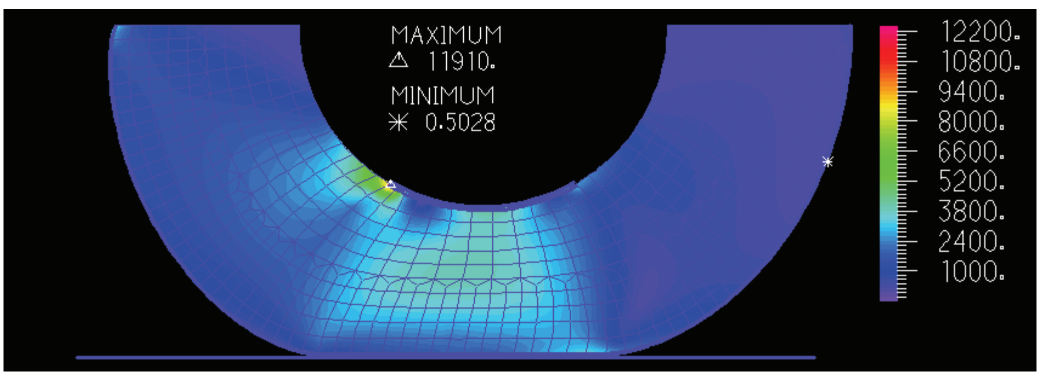

Fig. 13. Stress distribution in large gap model with oblique load (1.0 cm horizontal + 1.0 cm vertical)

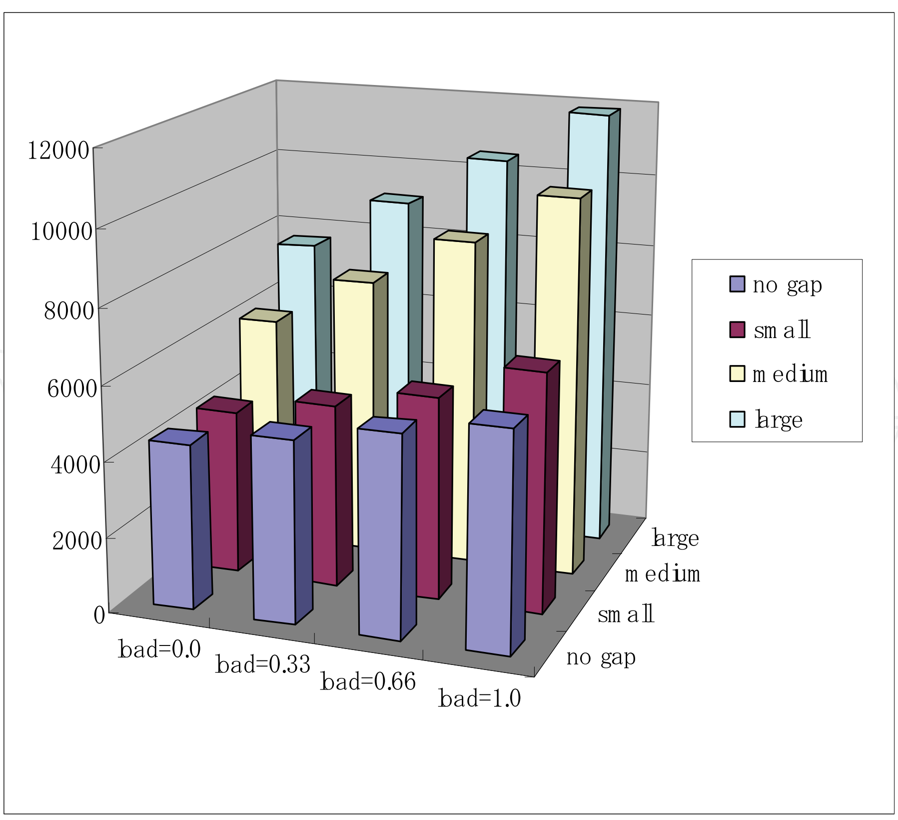

Fig. 14. Study 2: maximum stress in various horizontal load and gap size.

The results of the study 2 were summarized in a 3-D bar graph (Fig. 14). With the increment of horizontal load, biased stress concentration increased. As we noticed the gap size affect the stress distribution of pressure sore in the previous study, the horizontal load is also a big factor of worsening pressure ulcer.

6. Materials and methods (Study 3)

Basic design of FEA models were as the same as previous studies except cushion pads. For the study 3, the cushion pad was represented by a thin additional outer layer of soft tissue (Fig.15). It was assumed that the skin and the pad were in tight contact.
Poisson's ratio of the cushion pad was set to 0.49 (same as the soft tissue value). Five different values were used for Young's module of the cushion pad: 15 kPa (same as the soft tissue value), 7.5 kPa (1/2 the soft tissue value), 3.75 kPa (1/4 the soft tissue value), 1.87 kPa (1/8 the soft tissue value), and 0.93 kPa (1/16 the soft tissue value).
As a control, a model without a cushion pad was also analyzed. Effective stress was evaluated using a distribution map.

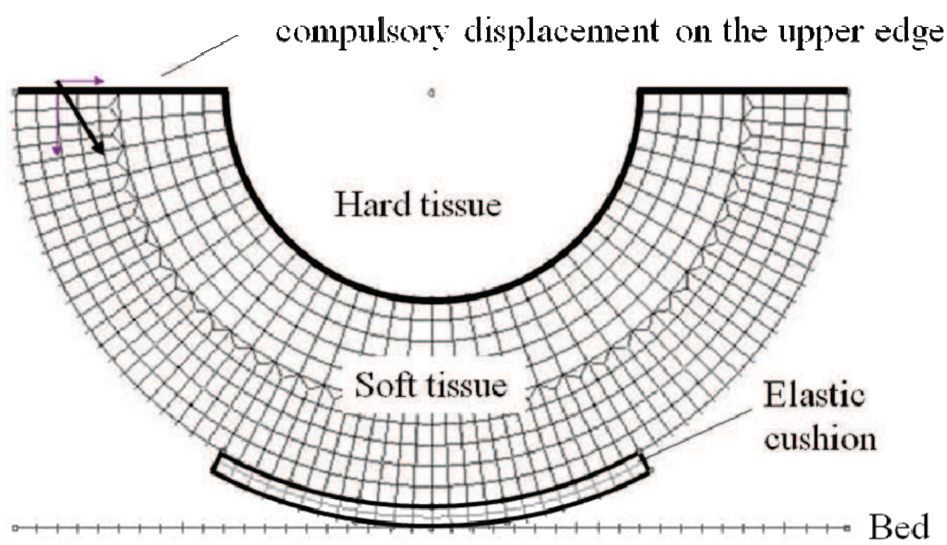

Fig. 15. Design of a model for study 3.

7. Results (Study 3)

Results of the FEA were summarized and visualized using a von-Mises stress distribution map. In the model without a cushion pad, 2 regions of concentration were observed. One region was at the boundary between the soft and hard tissue, and the other was at the centre of the soft tissue immediately below the hard tissue. The maximum values of effective stress were 5.83 kPa for the region at the boundary and 4.64 kPa for the region at the centre. These results are consistent with the previous findings.
All of the models with a cushion pad had a stress concentration pattern that was similar to that of the model without a cushion pad (Fig 16-18). That is, they each had 2 regions of concentration: one at the centre, and one at the boundary. The maximum values of effective stress decreased as Young's module of the cushion pad decreased (Fig 19). Thus, although

the stress concentration pattern was similar to that of the model without a cushion pad, the stress distribution became more diffuse as the cushion pad softness increased (i.e., Young's module decreased).

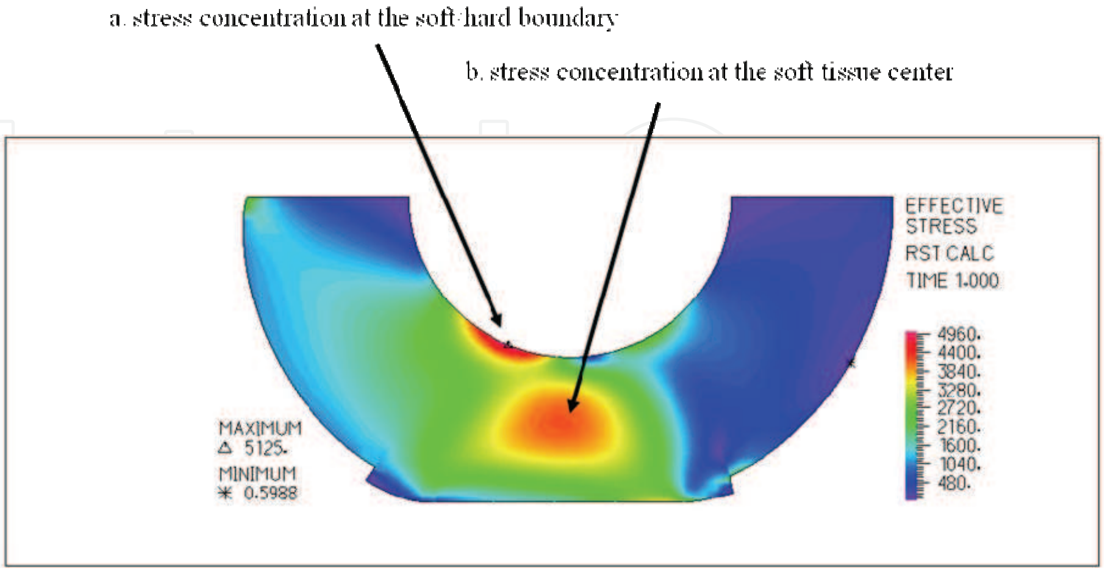

Fig. 16. Stress distribution with a same hardness cushion pad (E=15000 Pa)

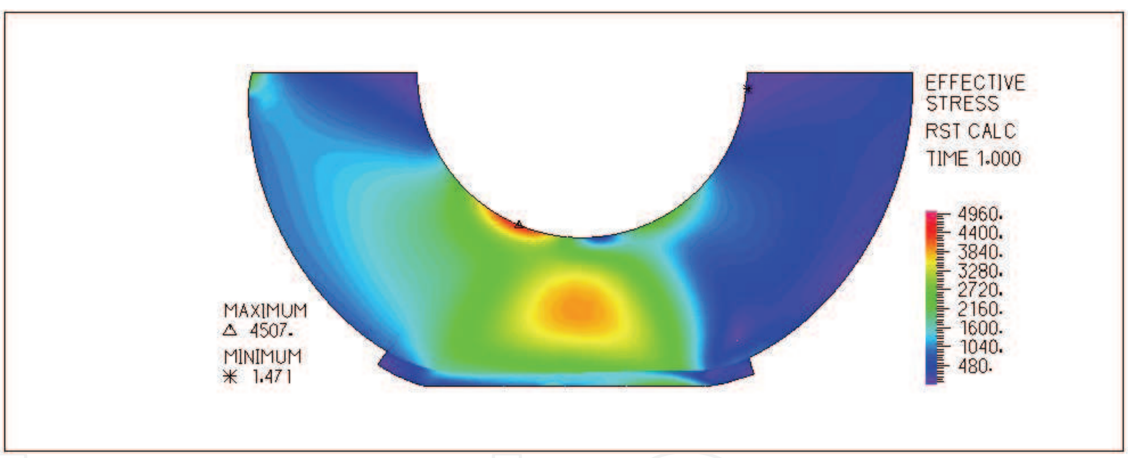

Fig. 17. Stress distribution with a quarter hardness cushion pad (E=3750 Pa)

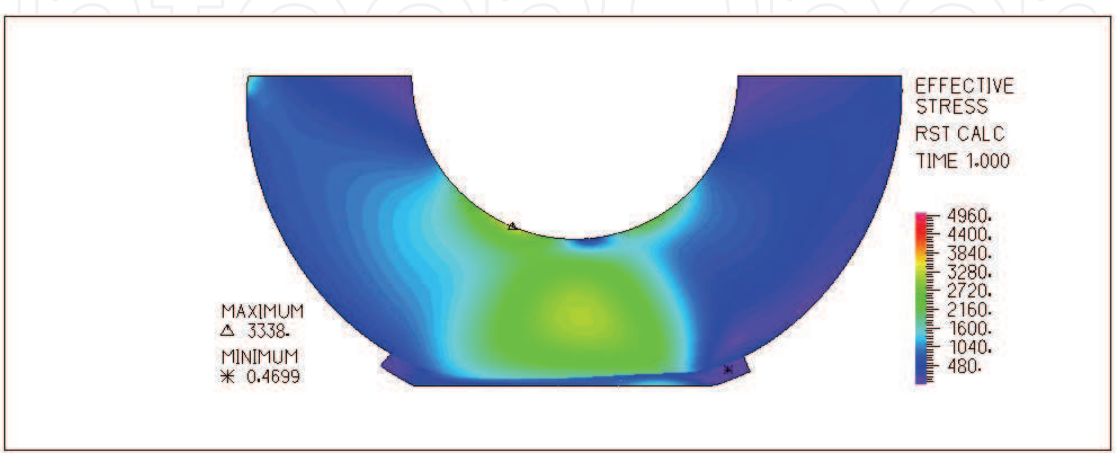

Fig. 18. Stress distribution with an 1/16 hardness cushion pad (E=973 Pa)

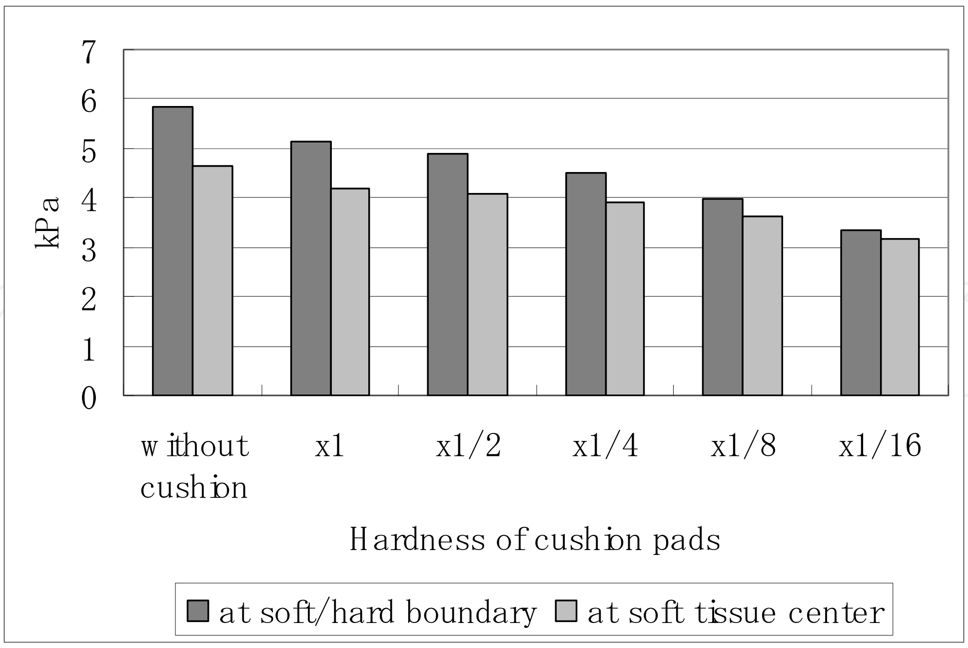

Fig. 19. Study 3: extreme maximum value of effective stress

8. Discussion

Chow and Odell made an axi-symmetric finite element model of a human buttock (Chow & Odell, 1978). The purpose of their study was to characterize stress patterns within the soft tissues of the buttock under different loading conditions. They modelled the buttock as a hemisphere of linear elastic isotropic soft tissue, with a rigid core to model the ischium. Honma and Takahashi evaluated the model of Chow and Odell, using the same conditions but with more precise calculation (Honma & Takahasi, 2001). Although that model was based on a hemisphere and our model was based on a cylinder, the basic design and shape of the 2 models are quite similar.

They mentioned stress concentration in the middle of the soft tissue and at the junction between the soft and hard tissue. In the present studies, we improved that model by converting it from axi-symmetric to non-symmetric, allowing analysis under non axi-symmetric conditions such as with an oblique load.

The results obtained from the first study using our non-undermining model were in good agreement with results obtained using the model of Chow and Odell. One of the purposes of the present analyses was to obtain data for use in further refinement of models of undermining. In the present models with gaps (representing undermining), stress was concentrated at the edges of the undermining. The maximum stress value increased with increasing size of undermining. These results suggest that after undermining develops, stress begins to concentrate at the edges of the undermining, and that this stress erodes the edges of the undermining, thus increasing the size of the undermining. Such a process is consistent with the clinical phenomena associated with formation of undermining.

Our second analyses were done for further modification for additional load from horizontal direction. Models with undermining showed increment of the stress concentration on the edges of the undermining in each combination of horizontal loads. Furthermore, shear stress

increased with horizontal load. In clinical condition, patient sometimes are moved and pushed in bed, so horizontal loads are tend to be exposed to such loads..
This result suggests a vicious circle of pressure sore that once some sized undermining emerges, stress concentration emergence on the edges of the undermining that will destroy the edges and increase the size of undermining by itself, and then more stress concentration occurs (Fig. 20). It may explain clinical phenomenon of formation and extension of undermining.

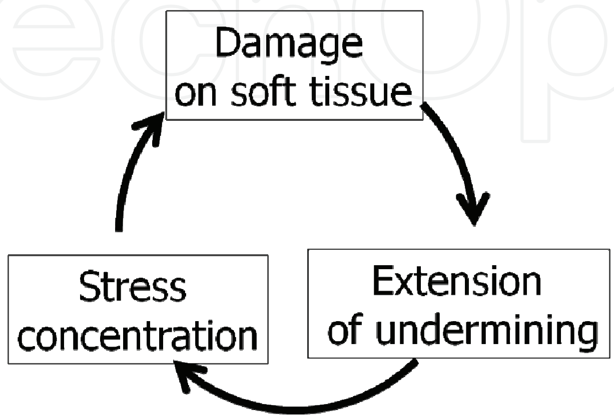

Fig. 20. A vicious circle of a pressure sore: Once some sized undermining emerges, stress concentration emerge on the edges of the undermining that will destroy the edges and increase the size of undermining by itself, then more stress concentration occurs.

A thick cushion pad is useful for reduction of stress concentration. There have been several studies (Souther et al., 1974; Garber & Krouskop, 1982; Minns et al., 1984; Delauter et al., 1984;) of the effectiveness of various cushions in reducing seat-interface pressures. The conclusion of those studies was that there seems to be a maximum effective cushion thickness, in terms of reduction of stress concentration. Those studies dealt mainly with vertical loads and cushion thickness.
Actual loads on patients in clinical settings are not limited to vertical loads due to gravity, but also include horizontal movement. A cushion that is thin in the vertical direction is not necessarily thin in the horizontal direction. In the third study, we simulated conditions in which a human is seated on a thin cushion pad with a variety of values of softness. The results suggest that a thin cushion pad reduces stress concentration, thus supporting the hypothesis. They also indicate that softer material is more effective at reducing stress concentration.

9. Conclusion

The finite element method can be used to calculate relationships between displacements and pressures or stresses. Thus, it can be used to determine the effects of various positions and motions of a patient on pressure sores, and this information can be used to prevent expansion of pressure sores. In the present study, although a very simple model was used for analysis, the results strongly suggest a particular mechanism for formation of large undermining in pressure ulcers.

10. References

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