

Biomechanics Analysis of Pressure Ulcer Using Damaged Interface Model between Bone and Muscle in the Human Buttock*

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Abstract

This paper aims at building up a computational procedure to study the bio-mechanism of pressure ulcer using the finite element method. Pressure ulcer is a disease that occurs in the human body after 2 hours of continuous external force. In the very early stage of pressure ulcer, it is found that the tissues inside the body are damaged, even though skin surface looks normal. This study assumes that tension and/or shear strain will cause damage to loose fibril tissue between the bone and muscle and that propagation of damaged area will lead to fatal stage. Analysis was performed using the finite element method by modeling the damaged fibril tissue as a cutout. By varying the loading directions and watching both tensile and shear strains, the risk of fibril tissue damage and propagation of the damaged area is discussed, which may give new insight for the careful nursing for patients, particularly after surgical treatment. It was found that the pressure ulcer could reoccur for a surgical flap treatment. The bone cut and surgical flap surgery is not perfect to prevent the bone-muscle interfacial damage.

Key words: Finite Element Method, Biomechanics, Pressure Ulcer, Interface Strain

1. Introduction

Pressure ulcers, also called bedsores or decubitus ulcers, result from prolonged pressure that cuts off the blood supply to the skin⁽¹⁾. This cut off of blood causes the surrounding skin cells to die. Only 2 hours of continuous physical pressure is enough to cause a pressure ulcer⁽²⁾. Low quality mechanical tissue properties can cause pressure ulcer, which are known to be caused by aging, wet conditions and a lack of nutrition⁽³⁾. The changes in tissue properties are hard to understand, and as a result most current research is focused more on treatment after a pressure ulcer occurs and designing special mattresses rather than studying the biomechanism even though it is very important for the prevention of pressure ulcers. The final goal of this research is to help prevent recurring pressure ulcers after surgical treatment by providing new insight into nursing care.

Pressure ulcers are classified into 4 stages in the medical field with Stage IV as the worst case⁽⁴⁾:

- Stage I: A reddened area on the skin that does not turn white when pressed. This indicates that a pressure ulcer is starting to develop.
- Stage II: The skin blisters or forms an open sore. The area around the sore

may be red and irritated.

- Stage III: The skin breakdown now looks like a crater. There is damage to the tissue below the skin.
- Stage IV: The pressure ulcer has become so deep that there is damage to the muscle and bone, and sometimes to tendons and joints.

Most pressure ulcers occur in situations where the subject is prone to a continuous mechanical load for a very long time, such as people who are bedridden or people who are dependent on a wheel chair ^(5,6). The human buttock is the area most prone to pressure ulcers for 2 reasons. First, the buttock is always used for support when a person sits or sleeps. Second, very little fat and muscle exist over the bone in the buttock ^(7,8).

In the very early stage of pressure ulcer formation, the tissues inside the body are damaged even though skin surface looks normal. However, the initial damaged location has not been clarified. This study assumes that the tension and/or shear strain first damages loose fibril tissue between the bone and muscle, and that propagation of the damaged area leads to more serious stages. The analysis was performed using the finite element method by modeling the damaged fibril tissue as a cutout. Then, how the damaged interface influences the pressure ulcer and how different loading directions affect the strain at the interface between the bone and muscle is discussed. However, there have been no observations of fibril tissue damage; therefore, there is no experimental value for its strength. The most notable feature of this study is the introduction of a cutout in the numerical model based on the above-mentioned biomechanical assumption and the comparison of the strains between models with and without a cutout.

Two numerical models were analyzed in this paper. One is a model of a healthy person, while the other is a model where a patient had a surgical treatment. Although there are several surgical methods, in this study, we choose to use the bone cut and surgical flap method ⁽⁹⁾ to explain our methodology. A surgical flap is made to cover a wound caused by a pressure ulcer using muscle from a different body part. Surgical treatment is used to treat patients with pressure ulcers, especially patients with stage IV pressure ulcers. Treatment for these patients is more aggressive since the process involves cleaning and dressing the diseased area and continued surgical repair, and then the surgical flap comes into place. The surgical flap is used because the muscle retains its own blood supply, thus aiding the recovery process. This study aimed to gain new insights into nursing care after surgery.

The assumptions of the biomechanism are described in the next section. The risk prediction method is described in section 2.2, followed by the finite element modeling. The 2 numerical models and the results are shown in chapter 3. The concluding remarks and future directions are summarized in sections 4.1 and 4.2, respectively.

2. Methods of Research

2.1 Assumptions of the Biomechanism

Figure 1(a) shows the CT image of a typical human buttock, which was analyzed in this paper. The bone and muscle are surrounded by fat and skin. The skin is neglected in the later finite element model because it is very thin and because the mechanical behaviors near the bone-buttock interface are the area of concern. Pressure ulcers often occur in the zone marked in red. As illustrated in Fig. 1(b), tiny loose fibril tissue connects the bone and muscle, and this fibril tissue deforms due to the external load.

It is well known that tissue death inside the body marks the beginning of a pressure ulcer, which propagates until the surface skin becomes red. However, the detailed biomechanism of what happens inside the body at this early stage has not yet been clarified.

This research assumes that tension and/or shear strain causes loose fibril tissue between the bone and muscle to be damaged and propagation of the damaged area will lead to more

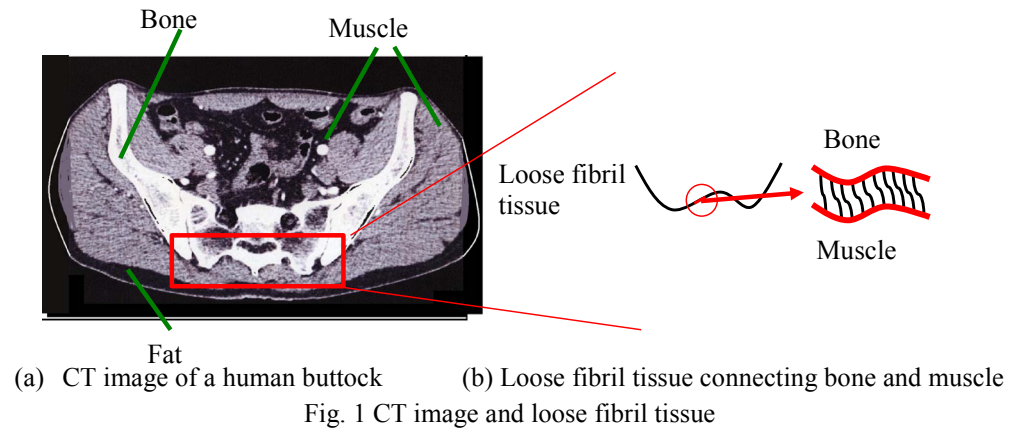


Fig. 1 CT image and loose fibril tissue

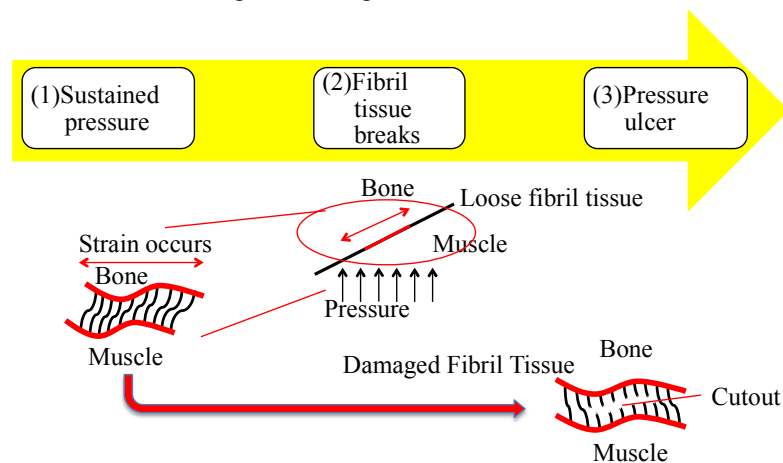


Fig. 2 Modeling assumption: how fibril tissue is damaged

serious stages. In Fig. 2, damaged fibril tissue is considered a cutout in the framework of continuum mechanics. Two damage types are assumed: mode I, which is due to excessive tensile strain, and mode II, which is due to shear strain.

Other phenomena, such as damage due to possible contact between muscle and bone, were not considered because they may occur after fibril tissue damage. The occurrence of fibril tissue damage as shown in Fig. 2 is the most important factor of interest, and this paper focuses on its risk prediction by introducing a cutout in the following numerical model. Since there have been no similar experimental or numerical studies, a strain-based damage criterion was assumed by comparing tensile or shear strains with and without a cutout.

2.2 Risk Prediction Method

First suppose a target body that is a body after surgery as mentioned in the Introduction. To estimate the safety or risk for the target body, the presence of damaged fibril tissue was assumed and modeled as a cutout. The location and the length of the damaged zone were the parameters in the risk prediction. To predict the possibility of propagation of the damaged zone, the strain at the tips of the cutout was calculated.

Note here that the strain should be evaluated in the local coordinate system denoted by t-n (tangential-normal) directions as shown in Fig. 3, not in the global coordinate system denoted by x-y. That is, the tensile strain ϵ_n and shear strain γ_{tn} that appear in the loose fibril tissue were evaluated. The compressive axial strain was not a matter of concern. Note also that the strain at the tip of the strain should be calculated as accurately as possible. Therefore, attention should be paid to the mesh generation along the bone-muscle interface.

Next, as a reference model, a healthy body was analyzed, and the strain was at the same

location where the cutout was in the target. In this study, 1 location for the cutout was fixed and its length was fixed to 4 mm, because this study is focused on describing the modeling methodology.

The loading direction was supposed to be the third parameter. The strain was analyzed with various loading cases ranging from 0° (shear) to 90° (perpendicular). Then, the maximum strain values for the load cases in the reference model were modified and denoted by $\epsilon_n^{\text{reference}}_{\text{max}}$ and $|\gamma_{\text{tn}}^{\text{reference}}|_{\text{max}}$. These values were used as reference criteria because they were lower than the real strength of the fibril tissue and because the damaged zone in the healthy body was not supposed to propagate with these values.

The strains at the tips of the cutout in the target body are denoted by $\epsilon_n^{\text{target}}$ and $|\gamma_{\text{tn}}^{\text{target}}|$. These values should be obtained by extrapolating the strain distribution along the interface. They can be replaced by the element strain values neighboring the cutout if the quality of the mesh is high enough.

If $\epsilon_n^{\text{reference}}_{\text{max}} \leq \epsilon_n^{\text{target}}$, then mode I propagation is possible. If $|\gamma_{\text{tn}}^{\text{reference}}|_{\text{max}} \leq |\gamma_{\text{tn}}^{\text{target}}|$, then mode II propagation is possible. Finally, the dangerous loading condition is predicted.

2.3 Finite Element Modeling

In this study, 2-dimensional static finite element analyses were performed under plane strain conditions for simplicity. In addition, assuming linear elasticity, the material properties for fat, muscle, and bone in Table 1⁽¹⁰⁾ were used.

A 4-node linear element was used, paying attention to the meshing near the cutout at the bone-muscle interface to obtain accurate strain distribution by controlling the distance between each element. The cutout itself was then simulated using a very thin element at the bone-muscle interface in the muscle region. However, in the muscle region, a very low Young modulus was used as shown in Table 2. The cutout was expressed by 1 element in the thickness direction; therefore, the strain distribution in the thickness direction was neglected. The cutout element properties were decided by looking at the muscle properties in Table 1. The Young modulus is 10^{-5} times smaller than muscle, which was determined by the authors' preliminary numerical tests.

Figure 4 shows a mesh with a cutout for a healthy human body based on the CT image in Fig. 1(a). This model was used as a criterion for the target surgery model that is described later. As mentioned above, a 4-mm cutout length was assumed at only 1 location, as shown

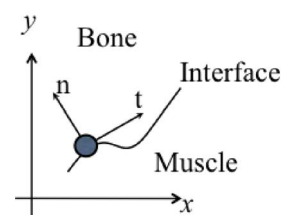


Fig. 3 Coordinate transformation

Table 1 Material Properties

Material Properties	Young Modulus (MPa)	Poisson's Ratio
Fat	8.0×10^{-2}	0.4
Muscle	7.5×10^{-2}	0.49
Bone	2.0×10^4	0.3

Table 2 Cutout Element Properties

Material Properties	Young Modulus (MPa)	Poisson's Ratio
Cutout	7.5×10^{-7}	0.49

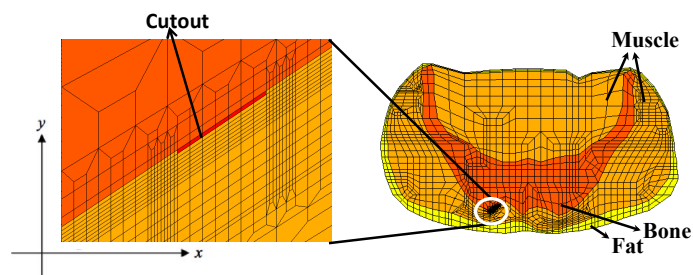


Fig. 4 Finite element mesh of the damaged interface for the healthy model

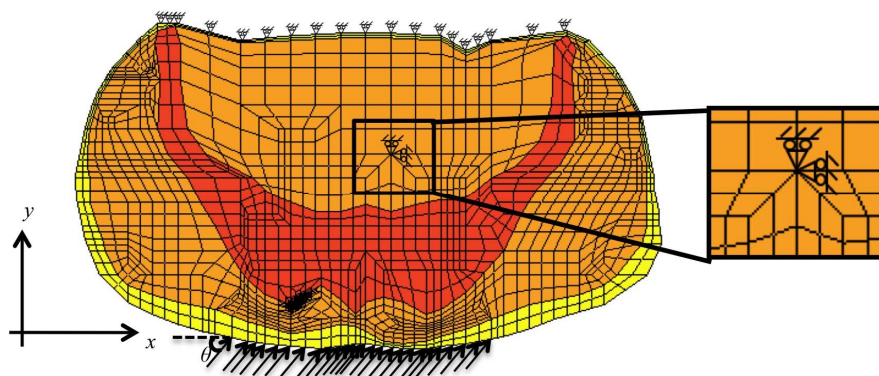


Fig. 5 Boundary and loading condition for the healthy model

in Fig. 4. Although it is known that the center location is the most dangerous due to the specific bone shape, this study will examine the strain and risk if the cutout is at different location.

As shown in Fig. 5, the upper side of the model was constrained in the y-direction, and a single node in the center of the model was fully constrained to escape the singularity of the stiffness matrix. Uniform pressure was assumed on the bottom side of the model. We assumed that the contact area between the buttock and the bed was a constant loading condition and unchanged. In this demonstrative analysis, the load value assumes a human weight of 70 kg in a 220 mm × 220 mm area with a loading angle variation denoted by θ in Fig. 5 from 0° (shear) to 90° (perpendicular). The numerical results in the following linear analyses are proportional to the load value. But, the load value is higher than real value because of the above assumption that all weight is applied only to the buttock. Needless to say, analyses for many load cases are easily performed when triangular factorization is used to solve the stiffness equation.

As was described in the Introduction, surgical treatment with bone cutting and a surgical flap is discussed from a mechanical viewpoint through the proposed risk prediction of a reoccurring pressure ulcer. Figure 6 shows the model after surgery. The outer contour of the human buttock was the same between the healthy and surgery models, because the same boundary condition should be given to both models.

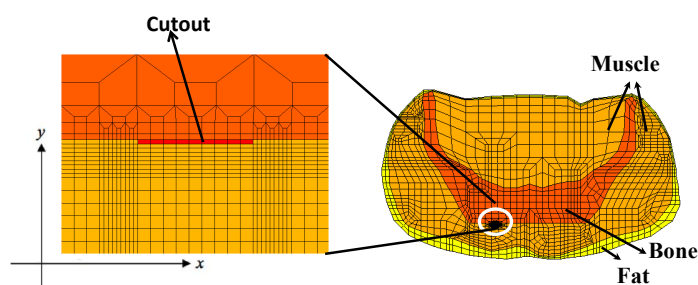


Fig. 6 Finite element mesh of damaged interface for after surgery model

3. Results and Discussion

3.1 Application to Healthy Model

According to the proposed algorithm, a healthy body model was analyzed first using the mesh shown in Fig. 5. A typical result for the distribution of tensile strain ε_y is shown in Fig. 7 for a case with a cutout under the loading condition $\theta=90^\circ$ (perpendicular). The strain distribution is shown in y-direction because strain in the n-direction is only used to evaluate the strain at the interface of the loose fibril tissue. We confirmed that the effect of the cutout was only seen near the cutout.

The strains transformed in the t-n directions at the left and right tips of the cutout were also plotted as blue (left tip) and red (right tip) lines in Figs. 8 and 9. The yellow bars indicate the strains at the same location for a case with no cutout. With no cutout, the tensile axial strain is very small. The maximum strains $\varepsilon_n^{\text{reference}}_{\text{max}}$ and $|\gamma_{tn}^{\text{reference}}|_{\text{max}}$ were determined from the result under the loading condition $\theta=0^\circ$. The dangerous loading conditions according to the risk prediction method in section 2.2 are shown in Figs. 8 and 9. This result may explain the fact that pressure ulcers can occur even in a healthy person if the fibril tissues between the bone and muscle are damaged and the damaged zone propagates. In other words, the cutout model can explain the scenario in Fig. 2.

Note that the plotted strain values for the cutout model are those at the center point of the most neighboring element to the left or right tip of the cutout, after deep investigation of the strain distribution and the extrapolated strain values at the tips of the cutout. Figure 10 shows a typical result for the extrapolation of strains. The absolute values of the extrapolated strains were generally higher than the plotted ones in Figs. 8 and 9, except the shear strain for $\theta=0^\circ$ shown in Fig. 10(b). In this study, the strain values at the neighboring element were employed because the post processing was much easier.

3.2 Risk Prediction after Surgery

In this section, the model for after surgery described in the Introduction and shown in Fig. 6 is analyzed. A 4-mm cutout was assumed in the same location in x coordinate system so that the same reference value could be used.

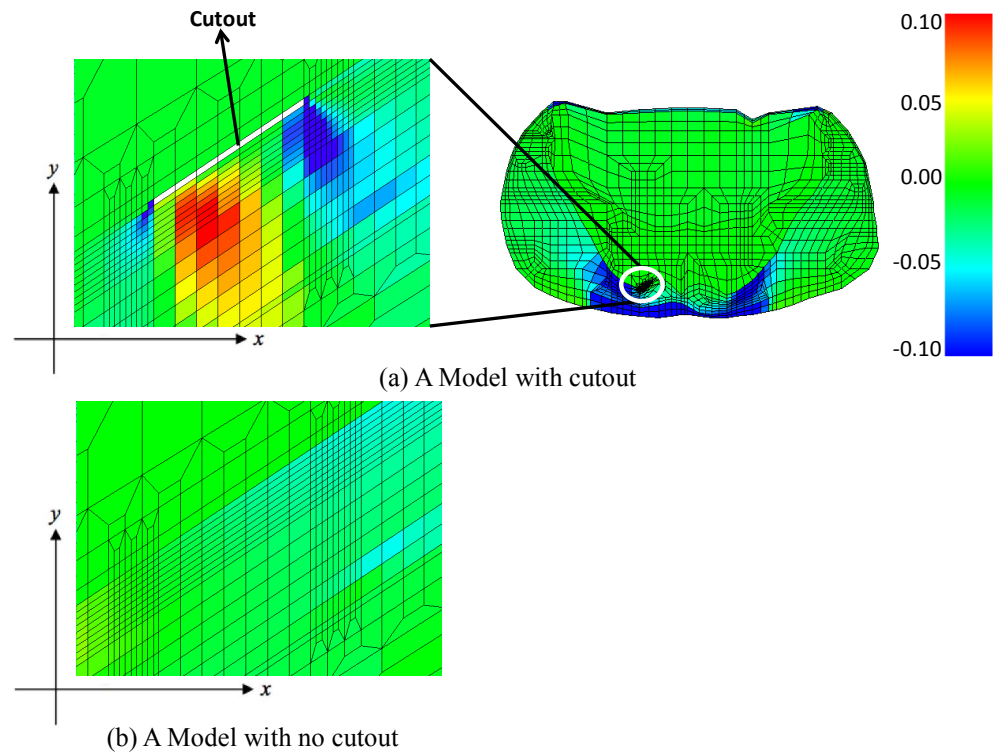


Fig. 7 Distribution of ε_y for the healthy body model (loading direction $\theta=90^\circ$)

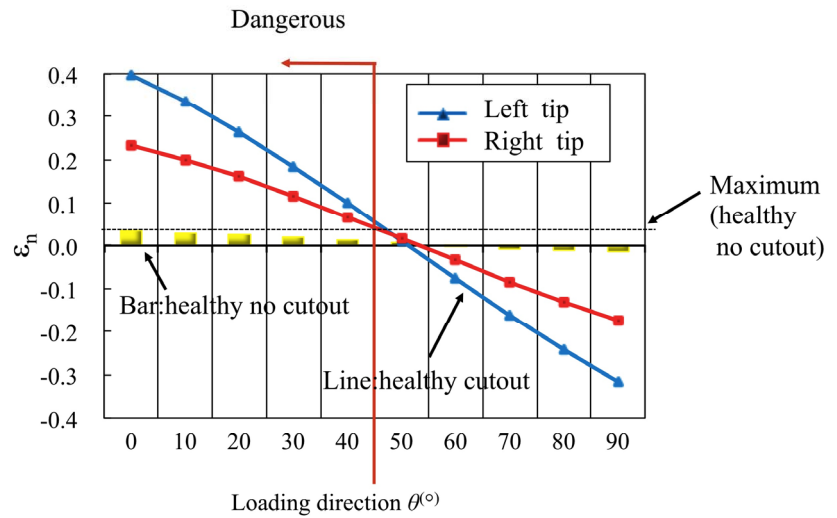


Fig. 8 ε_n for the healthy body model

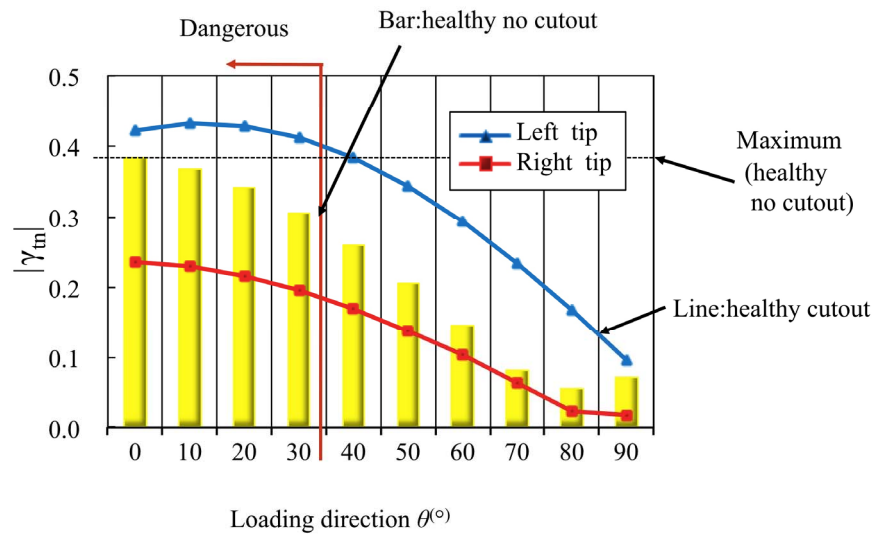
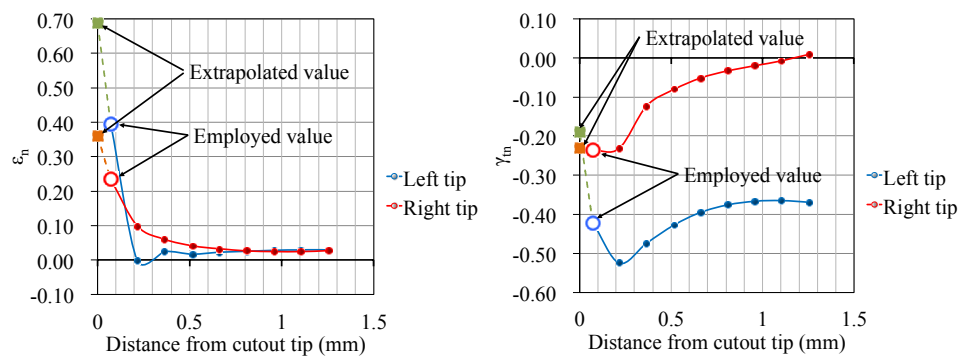


Fig. 9 $|\gamma_{tn}|$ for the healthy body model



(a) Extrapolation of ε_n at 0°

(b) Extrapolation of $|\gamma_{tn}|$ at 0°

Fig. 10 Typical result for the extrapolation of strains for the healthy model

Here again, the strain values of the elements neighboring the cutout tips were used instead of the extrapolated values shown in Fig. 11. In this analysis, the absolute values of the extrapolated strains were larger or almost the same. Therefore, the choice of the

extrapolated value or the value of the neighboring element did not influence the conclusion. The strains at the left (blue line) and right (red line) tips of the cutout in the model after surgical operation are plotted in Figs. 12 and 13 and compared with the reference values. The axial strain was mostly negative, but relatively high tensile strain was found at the right

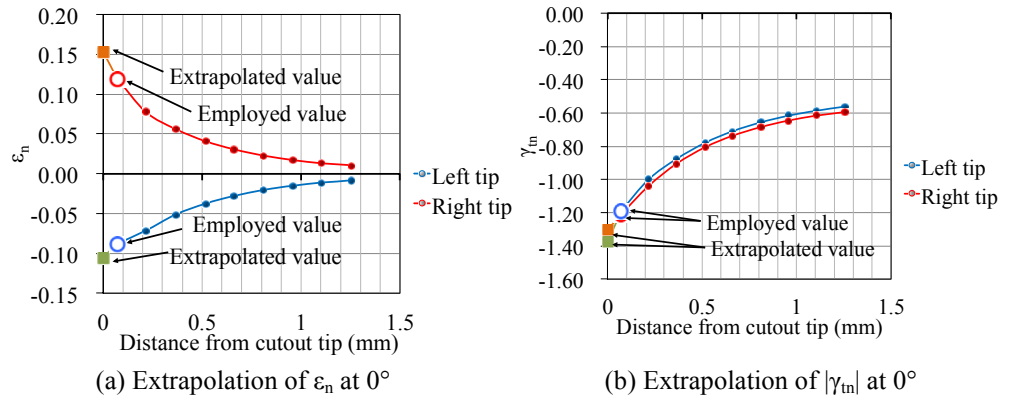


Fig. 11 Typical result for the extrapolation of strains for the after surgery model

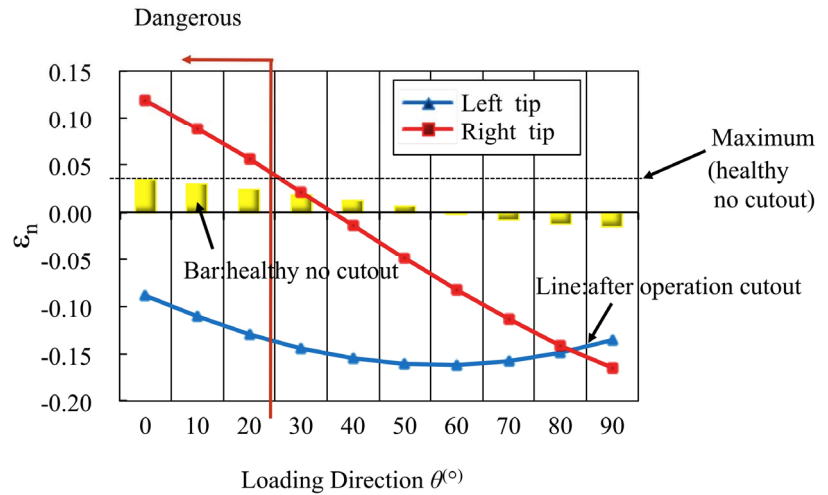


Fig. 12 ε_n for the after surgery model with cutout

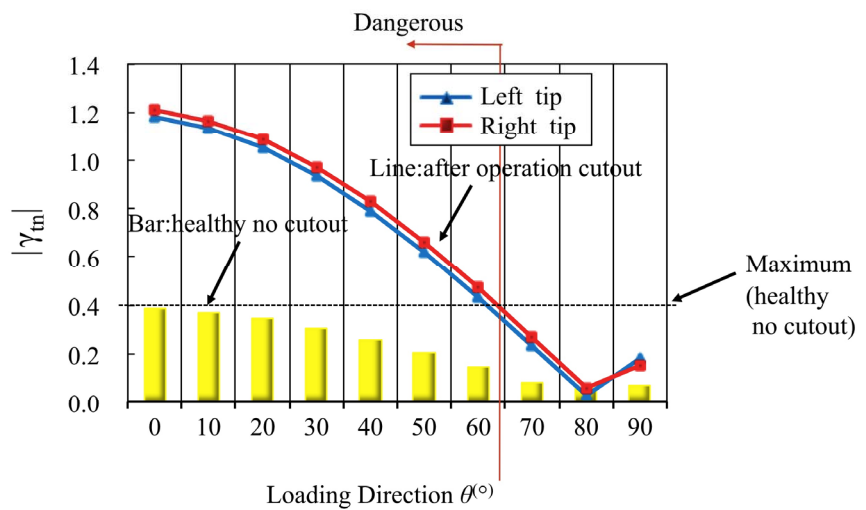


Fig. 13 $|\gamma_{tn}|$ for the after surgery model with cutout

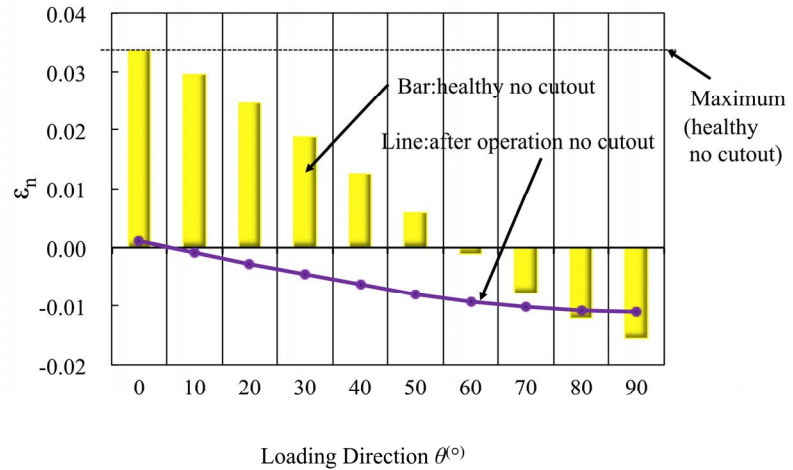


Fig. 14 ϵ_n for the after surgery model without cutout

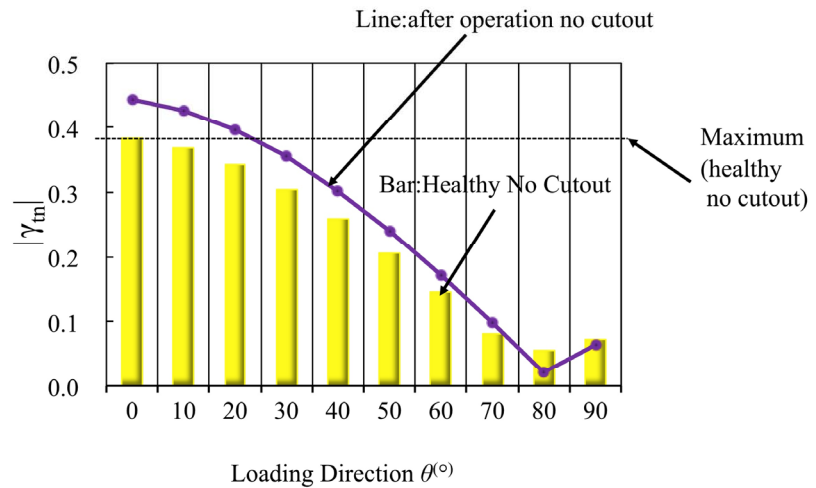


Fig. 15 $|\gamma_{tn}|$ for the after surgery model without cutout

tip of the cutout under the severe shear loading direction, which implies mode I propagation. Moreover, extremely high strain was observed for wider loading angle range, which implies mode II propagation.

In summary, a pressure ulcer may recur after bone cut plus surgical flap treatment if severe shear loading is repeatedly applied to a patient, as a result of mode II type fibril tissue damage and damaged area propagation in either mode I or mode II. Note that much higher shear strain can occur than in the natural configuration once interfacial damage occurs.

This is consistent with clinical fact, because some cases have been reported where a patient had a recurring pressure ulcer after surgical flap treatment^(11,12,13). In these cases, the numerical result implies that if a severe shear load is never applied due to special nursing care of the patient, then the risk of a recurring pressure ulcer decreases.

To further describe the above results, the influence of the cutout on the strain was analyzed using an after surgery model with no cutout. The results are shown in Figs. 14 and 15. The axial strains were negative for all loading angles and they were much lower than the healthy model. The shear strains in Fig. 16 were nearly the same as the ones for the healthy model. It was thought that the bone cut contributed to this result. In addition, the larger muscle mass from the surgical flap operation was supposed to work like a cushion. However, once fibril tissue damage occurs, the strains for this configuration may increase

and can lead to pressure ulcer recurrence. The numerical results suggest that it may occur under severe shear loading conditions in patients receiving nursing care. In conclusion, the bone cut and surgical flap surgery is not the perfect treatment for the prevention of bone-muscle interfacial damage under specific loading conditions.

4. Conclusion

4.1 Concluding Remarks

In this paper, a numerical approach was proposed to clarify the biomechanism of the beginning of pressure ulcer formation inside the human body. The most notable feature of this study lies in the assumption that damage of loose fibril tissue between bone and muscle is very influential. The key points from the standpoint of computational mechanics are that the fibril tissue damage is modeled as a cutout, and that the risk prediction method is proposed by introducing the cutout. The tensile and shear strains at the tips of the cutout were analyzed by 2D linear static models in plane strain condition and compared with those for a healthy reference body with no cutout. Then, a simple procedure to estimate the risk was proposed so that a medical doctor can perform the analysis.

In the application of this method to a model after bone cut and surgical flap operation, the possibility of a recurring pressure ulcer, which is a clinical fact, was predicted under the severe shear loading that could occur in patients receiving nursing care. It was thought that a fatigue fracture might occur in the tiny fibers by repeated shear loading. Therefore, our results agree with the clinical fact of recurring pressure ulcers in patients after surgery. Therefore, it will be important to intensively and experimentally study loose fibril tissue damage.

4.2 Future Studies

Three parameters, the location of the cutout, its length, and loading direction, were pointed out in this paper. However, only the loading direction was considered in the demonstrative analyses. The sensitivity of the location and the length of the cutout should be analyzed in the future. In pursuit of this, a future study should be devoted to decreasing the meshing efforts, for instance, by the finite element mesh superposition technique^(14,15,16). Using this technique, a local mesh representing the cutout is generated independently on a global buttock model and is easily superimposed onto the global model. A stochastic mesh superposition method that can automatically superimpose the same local model onto a different location on the global model with a minimum increase in the computational cost is under development. In addition, use of the mesh superposition method will enable us to analyze 3-dimensionally.

Many simplifications were made in the 2-dimensional plane strain analysis. The contact between the body and bed should be analyzed in the next step. It will provide a more realistic loading condition and enable modeling of other surgery cases with different configurations. However, the more important issue is to consider the sensitivities of the loading condition. In particular, to use this analysis to gain new insight not for bed mattress design but for nursing to prevent pressure ulcers, it is necessary to measure the load in nursing.

Phenomena other than the fibril tissue damage by tension and shear strains were neglected; however, the contact between bone and muscle must be studied by nonlinear analysis. Experimental studies are expected, including the observation of fibril tissue damage, the measurement of its strength, the material properties of muscle, and so on.

Dynamic analysis to examine the fatigue fracture implied in this paper is also of interest in the near future.

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References

- (1) Bansal, C., Scott, R., Stewart, D., Cockerell, C.J., *Decubitus ulcers: A review of the literature*, International Journal of Dermatology, 44(2005), pp.805-810.
- (2) Reddy, M., Gill, S.S., Rochon, P.A., *Preventing pressure ulcers: systematic review*, The Journal of the American Medical Association, 296(2006) pp.974-984.
- (3) Schoonhoven, L., Defloor, T., Grypdonck, M.H.F., *Incidence of pressure ulcers due to surgery*, Journal of Clinical Nursing, 11(2002), pp.479-487.
- (4) Brem, H., Lyder, C., *Protocol for the successful treatment of pressure ulcers*, The American Journal of Surgery, 188(2004), pp.9S-17S.
- (5) Bouten, C.V., Oomens, C.W., Baaijens, F.P., Bader, D.L., *The etiology of pressure sores: Skin deep or muscle bound?*, Archives of Physical Medicine and Rehabilitation, 84(2003), pp.616-619.
- (6) Makhssous, M., Lim, D., Hendrix, R., Bankard, J., Rymer, W.Z., Lin, F., *Finite element analysis for evaluation of pressure ulcer on the buttock: development and validation*, IEEE Transactions on Neural Systems and Rehabilitation Engineering, 15(2007), pp.517-525.
- (7) Ba' Pham, Stern, A., Chen, W., Sander, B., John-Baptiste, A., Thein, H., Gomes, T., Wodchis, W.P., Bayoumi, A., Machado, M., Carcone, S., Krahn, M., *Preventing pressure ulcers in long-term care*, Archives of Internal Medicine, 171(2011), pp.1839-1847
- (8) Linder-Ganz, E., Shabshin, N., Itzhak, Y., Gefen, A., *Assessment of mechanical conditions in sub-dermal tissues during sitting: A combined experimental-MRI and finite element approach*, Journal of Biomechanics, 40(2007), pp.1443-1454.
- (9) Romanelli, M., Clark, M., Cherry, G., Colin, D., Defloor, T., *Science and practice of pressure ulcer management*, (2006), pp.128-132, Springer.
- (10) Yamamoto, Y., Doi, Y., Akiyama, Y., Izumi, Y., Kimura, H., Nishijima, S., *Biomechanical simulation for prevention of pressure ulcers (1.FEM simulation)*, Transactions of Japanese Society for Medical and Biological Engineering, 46(2008), pp.489-494 (in Japanese).
- (11) Ahluwalia, R., Martin, D., Mahoney, J. L., *The operative treatment of pressure wounds: a 10-year experience in flap selection*, International Wound Journal, 7(2010), pp.103-106.
- (12) Mandrekas, A. D., Mastorakos, D. P., *The management of decubitus ulcers by musculocutaneous flaps: a five-year experience*, Ann Plast Surg 28(1992), pp.167-74.
- (13) Tavakoli, K., Rutkowski, S., Cope, C., Hassall, M., Barnett, R., Richards, M., Vandervord, J., *Recurrence rates of ischial sores in para- and tetraplegics treated with hamstring flaps: an 8-year study*, Br J Plast Surg. 52(1999), pp. 476-479.
- (14) Takano, N., Zako, M., Ishizono, M., *Multi-scale computational method for elastic bodies with global and local heterogeneity*, Journal of Computer-Aided Materials Design, 7(2000), pp.111-132.
- (15) Takano, N., Zako, M., Okazaki, M., *Efficient modeling of microscopic heterogeneity and local crack in composite materials by finite element mesh superposition method*, JSME International Journal, Series A, 44(2001), pp.602-609.
- (16) Takano, N., Zako, M., Okuno, Y., *Multi-scale finite element analysis of porous materials and components by asymptotic homogenization theory and enhanced mesh superposition method*, Modelling and Simulation in Materials Science and Engineering, 11(2003), pp.137-156.