# Can Functional Electrical Stimulation for Pressure Ulcer Prevention reduce efficiently the Incidence of Deep-Tissue Injury?

Dohyung Lim and Keyoung Jin Chun

***Abstract*****—**In the United States, 1.4 million people who rely on wheelchairs for mobility develop serious pressure ulcer (PU) at pressure areas such as ischium and sacrum due to prolonged sitting. Recently, functional electrical stimulation (FES) has been proposed as a means to prevent development of PU through the redistribution and the reduction of the internal stresses within the deep tissue of the buttock, which were achieved by the increase of the muscle thickness, particular in the gluteus maximus. However, rare information about how much reduction of the incidence of deep-tissue injury in the FES application for PU prevention are positively induced through the internal stress relief resulting from the alteration of the muscle thickness achieved by the FES is currently available. The objective of the current study was therefore to identify if the FES application may efficiently reduce the incidence of deep-tissue injury, by evaluating a degree of the internal stress relief through the alteration of the gluteus maximus muscle thickness using Finite Element (FE) analysis combined with MRI image analysis. Four FE models were created through 3D reconstruction model made from buttock-thigh MRI images, which were obtained in an actual sitting posture of a specific subject. The internal von Mises stresses within the gluteus maximus were computed and analyzed with alterations of the gluteus maximus muscle thickness considered in the current study. The results showed that the distributions of the high internal von Mises stresses within the gluteus maximus were gradually decreased with the increase of the gluteus maximus muscle thickness. However, the maximum von Mises stresses within the gluteus maximus were irregularly changed. The current study confirms that the internal von Mises stress relief effects of the FES application for PU prevention may have substantial benefits in terms of reduction of the incidence of the deep-tissue injury. It can be concluded that incorporating the FES system into a rehabilitation and treatment program for individuals who have sitting-related PU wounds may promote the healing progress while maintaining their mobility.

***Keywords*** **—** Deep-Tissue Injury, Finite Element Analysis, Functional Electrical Stimulation, Internal Stress Relief, Muscle Thickness Change, Pressure Ulcer.

## I. INTRODUCTION

IN the United States, many of the 1.4 million people who rely on wheelchairs for mobility develop serious tissue breakdown, i.e., pressure ulcer (PU), at pressure areas such as the ischium and trochanter due to prolonged sitting [1-5]. Generally, it is accepted that the primary etiology of the PU on the buttock is prolonged external sitting loading. Therefore, for a breakthrough in prevention of PU, it is necessary to obtain a better understanding of mechanical responses on the buttock by prolonged external sitting loading. This will provide design criteria for optimal pressure relieving strategies.

Recently, functional electrical stimulation (FES) has been proposed as a means to prevent PU development through the redistribution and the reduction of the internal stresses within the deep tissue of the buttock, which were achieved by the increase of the muscle thickness, particular in the gluteus maximus [6-13]. The therapeutic effects of the FES application for PU prevention were first observed early in the 20th century and this technique has been widely employed as a clinical treatment over recent decades [6-13]. Taylor et al [6] found that subjects who received the FES exhibited positive changes in regional tissue health, i.e., significant increases in thigh blood flow and in quadriceps muscle depth. Levine et al [7-10] found that the FES application on the gluteus maximus increased the regional blood flow and the decreased sizable pressure under the ischial tuberosity with the redistribution of the pressure occurring over other parts of the seating surface. Bogie et al [11-13] showed that the FES application for PU prevention exhibited positive changes in tissue health through statistically significant reduction in the ischial interface pressure, increase in the gluteus maximum muscle thickness, and derivation of dynamic weight shifting while seated in the wheelchair. However, rare information about how much the therapeutic effects of the FES application for PU prevention are positively induced through the internal stress relief resulting from an alteration of the muscle thickness achieved by the FES is currently available.

The objective of the current study was therefore to evaluate a degree of the internal stress relief through an alteration of the gluteus maximus muscle thickness, by using Finite Element (FE) analysis combined with MRI image analysis.

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## II. MATERIALS AND METHODS

### A. *FE Model Development*

MRI examination of the buttocks was performed for a healthy subject (24yr, 165.0cm, 70.0kg) at one real sitting position (576x576 matrix, 35 cm FOV, 288 slices, 0.6 mm thickness). A FE model as a healthy model was then created based on 3D reconstruction model of the buttock-thigh structure obtained from MRI examination (Fig. 1).

Contours of anatomic structures (femur, pelvis, skin, fat and five muscle groups) were identified and digitized from images obtained from MRI examination. The digitized information was then translated into HyperMesh (Altair Engineering, Inc., Troy, MI) to create FE mesh. The final FE model consisted of 453,502 four-node modified tetrahedral solid elements for the pelvis, femur, inner side of the skin, fat and five muscle groups, and 33,924 three-node triangle membrane elements for the outer side of the skin (Fig. 1).

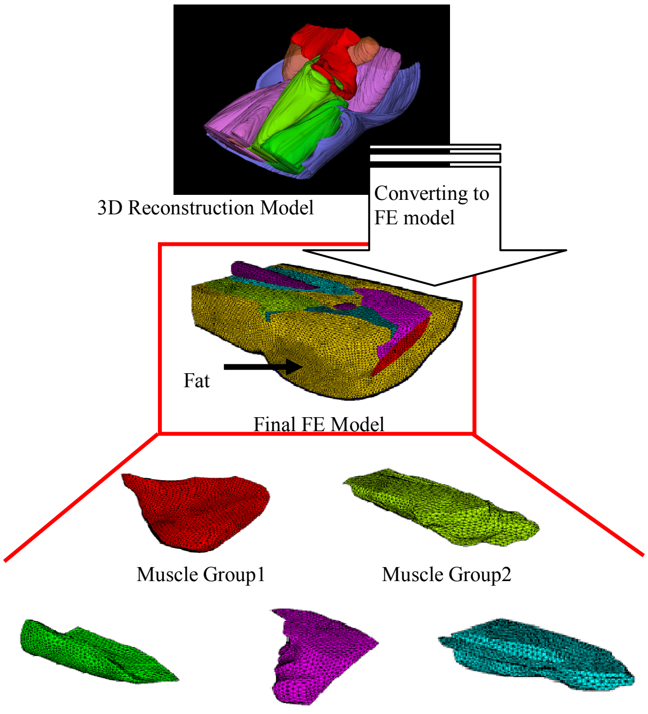


Fig. 1 Three-dimensional reconstruction model (left on the top) and final FE model (right on the top) and its structural elements (bottom) for the muscle groups considered in the current study.

### B. *Representation of Gluteus Maximus Muscle Thickness Change*

Based on the healthy FE model above, three modified FE models were developed to represent status of the buttock before the FES application as a reference model, after the regular short-term FES application as a mild treatment model, and after the regular long-term FES application as an effective treatment model (Fig. 2). Here, the effect of the FES application was represented as the increase of the gluteus maximus muscle thickness below the ischial tuberosity.

For the reference model, the thickness of the gluteus maximus muscle below the ischial tuberosity was decreased to 40% relative to that of the healthy model. The thicknesses of the gluteus maximus muscles below the ischial tuberosity for the mild and the effective treatment models were increased to 30% and 60% relative to that of the reference model, respectively. Here, the alterations of the muscle thicknesses for the models were determined based on the findings obtained from the clinical evaluations reported by Taylor et. al. [6], Levine et al. [7-10], Bogie et. al. [11-13].

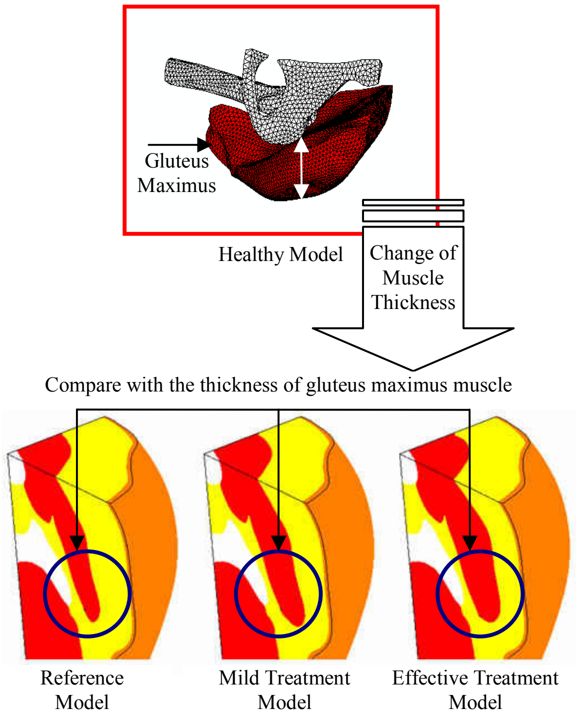


Fig. 2 Reference, mild treatment and effective treatment models modified from the healthy model.

### C. *Material Model for FE Model*

First order Ogden model as in Eq. (1), which can account for large deformation behaviors of materials, was employed for skin, fat and muscle and static analysis was performed.

$$W = \sum_{i=1}^{N} \frac{2\mu_i}{\alpha_i^2}(\bar{\lambda}_1^{\alpha_i} + \bar{\lambda}_2^{\alpha_i} + \bar{\lambda}_3^{\alpha_i} - 3)^i + \sum_{i=1}^{N} \frac{1}{D_i}(J^{el} - 1)^{2i} \quad (1)$$

where $W$ is the strain energy per unit of reference volume; $\mu$, $\alpha$, and $D_i$ are the temperature-dependent material parameters; $J$ is the total volume ration; $J^{el}$ is the elastic volume ration; and the deviatoric stretches are represented by following Eq. (2).

$$\overline{\lambda}_i = J^{-1/3}\lambda_i \qquad (2)$$

where $\lambda_i$ are the principal stretches.

The material parameters for skin, fat and muscle were determined based on values obtained from literature [14]. Here, $D_i$ was regarded as zero for all soft-tissues, based on an fact that the materials were nearly incompressible (*Poisson ratio* $\cong$ *0.495*). Stress-strain curves determined by Ogden Hyperelastic Material Model and Material Coefficients used in the current study were shown in Fig. 3.

Contours of anatomic structures (femur, pelvis, skin, fat and five muscle groups) were identified and digitized from images obtained from MRI examination. The digitized information was then translated into HyperMesh (Altair Engineering, Inc., Troy, MI) to create FE mesh. The final FE model consisted of 453,502 four-node modified tetrahedral solid elements for the pelvis, femur, inner side of the skin, fat and five muscle groups, and 33,924 three-node triangle membrane elements for the outer side of the skin (Fig. 1).

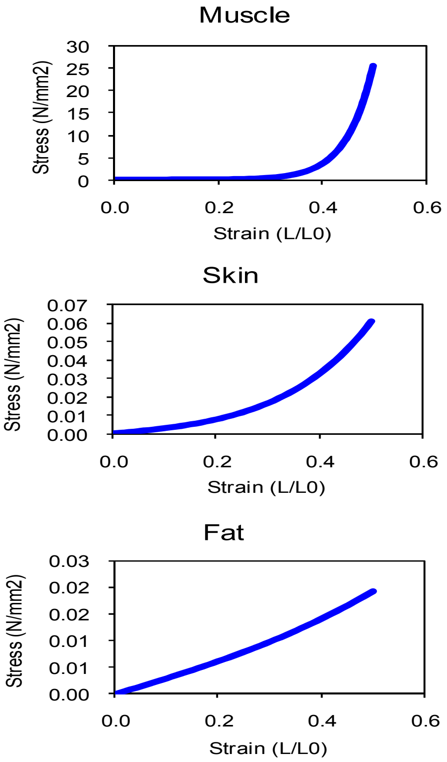


Fig. 3 Stress-strain curve determined by Ogden Hyperelastic Material Model and Material Coefficients used in the current study.

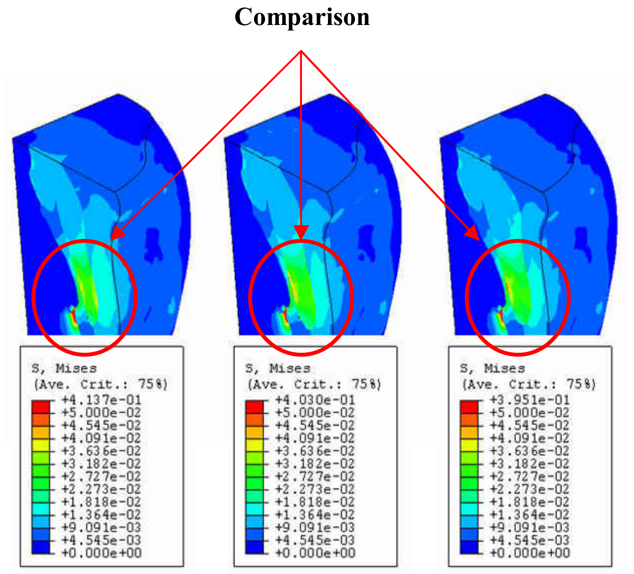
## D. *FE Model Simulation and Analysis*

The developed FE models were simulated considering the realistic boundary (constraints against medial-lateral and longitudinal motions) and loading conditions (sitting loading, skin tension, and muscle tone) and solved by ABAQUS 6.5package (ABAQUS, Inc., Providence, RI USA).

The internal von Mises stresses within the gluteus maximus were computed and analyzed with alterations of the gluteus maximus muscle thickness considered above.

## III. Results

The results showed that the distributions of the high internal von Mises stresses within the gluteus maximus were gradually decreased with the increase of the gluteus maximus muscle thickness (Figs. 4 and 5). However, the maximum von Mises stress within the gluteus maximus was irregularly changed. The maximum von Mises stresses within the gluteus maximus for the reference, the mild treatment, and the effective treatment models were 54.5MPa, 69.7MPa, and 60.8MPa, respectively.



Reference Model Mild Treatment Model Effective Treatment Model

Fig. 4 Internal von Mises stress distribution on the whole buttock-thigh structure. The high internal von Mises stress distribution was gradually decreased with the increase of the gluteus maximus muscle thickness.

## IV. Discussions and Conclusions

The current study may be valuable by identifying for the first time the therapeutic effect, i.e., internal von Mises stress relief by muscle thickness increase, of the FES application for PU prevention. This finding may contribute to designing a prevention or treatment program for individuals with sitting-related PU wounds. It also can be concluded that incorporating the FES system into the rehabilitation and treatment program may promote the healing progress while maintaining their mobility.

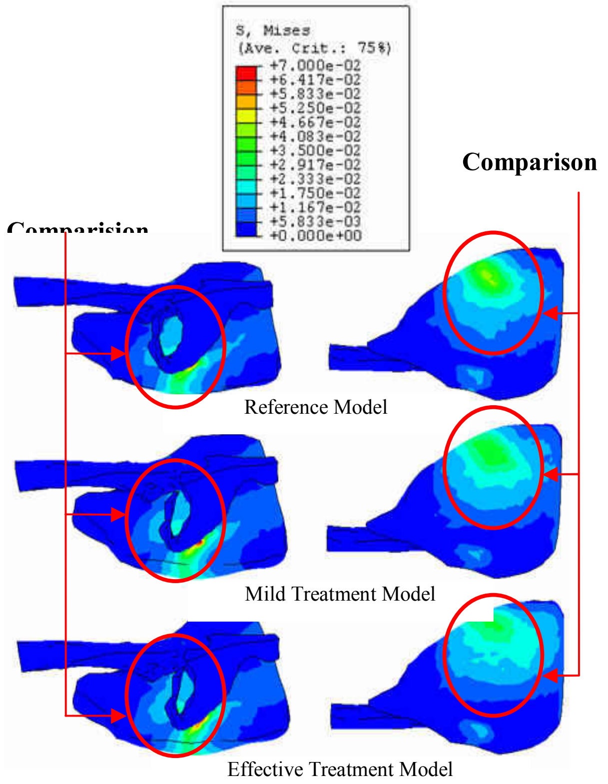


Fig. 5 Internal von Mises stress within the gluteus maximus. The high internal von Mises stress distribution was gradually decreased with the increase of the gluteus maximus muscle thickness.

The FE analysis as non-invasive and non-destructive approach is currently a unique tool allowing examination of the mechanical responses within the deep tissues of the buttock to external sitting loads. Several such FE models have been developed to provide some insight about the mechanical responses in the deep tissues of the buttock subjected to sitting load [3-4, 14-19]. However, several intrinsic weaknesses are associated with these models. First, the geometry and the material characteristics were overly simplified to approximate the complicated anatomical structure. Second, for those models of which the geometry established based on accurate MRI recording, the MRI measurements were not performed in a setup which was close to real sitting, but in supine posture [20], which differs intuitively from that in sitting posture in the sense of joint configuration. However, our FE models developed considering the complicated anatomical structures composed of the buttock in the actual sitting posture may exhibit more reasonable results comparing with those of other studies.

## REFERENCES

[1] D. Brienza, P. Karq, M. Geyer, S. Kelsey, E. Trefler, “The relationship between pressure ulcer incidence and buttock-seat cushion interface pressure in at-risk elderly wheelchair users,” Arch. Phys. Med. Rehabil., vol. 82, pp. 529-533, 2001

[2] C.L. Gawron, “Risk factors for and prevalence of pressure ulcers among hospitalized patients,” J Wound Ostomy Continence Nurs., vol. 21, pp. 232-240, 1994

[3] M. Makhsous, D. Lim, R. Hendrix, J. Bankard, W.Z. Rymer, F. Lin, “Finite element analysis for evaluation of pressure ulcer on the buttock: development and validation, IEEE Trans Neural Syst Rehabil Eng., vol. 15, pp. 517-525, 2007

[4] D. Lim, F. Lin, R. Hendrix, B. Moran, C. Fasanati, M. Makhsous, “Evaluation of a new sitting concept designed for prevention of pressure ulcer on the buttock using finite element analysis, Med Biol Eng Comput., vol. 45, pp. 1079-1084, 2007

[5] M. Mimura, T. Ohura, M. Takahashi, R. Kajiwara, N. Ohura Jr., “Mechanical leading to the development of pressure ulcers based on shear force and pressure during a bed operation: influence of body types, body positions, and knee positions,” Wound Repair Regen., vol. 17, pp. 789-796, 2009

[6] P. Taylor, D. Ewins, B. Fox, D. Grundy, I. Swain, “Limb blood flow, cardiac output and quadriceps muscle bulk following spinal cord injury and the effect of training for the Odstock functional electrical stimulation standing system,” Paraplegia, vol. 31, pp. 303-310, 1993

[7] S. Levine, R. Kett, P. Cederna, L. Bowers, S. Brooks, “Electrical muscle stimulation for pressure variation at the seating interface.” J Rehabil Res Dev., vol. 26, pp. 1-8, 1989

[8] S. Levine, R. Kett, P. Cederna, S. Brooks, “Electric muscle stimulation for pressure sore prevention: tissue shape variation,” Arch Phys Med Rehabil., vol. 71, pp. 210-215, 1990

[9] S. Levine, R. Kett, M. Gross, B. Wilson, P. Cederna, J. Juni, “Blood flow in the gluteus maximus of seated individuals during electrical muscle stimulation,” Arch. Phys. Med. Rehabil., vol. 71, pp. 682-686, 1990

[10] S. Levine, R. Kett, M. Ferguson-Pell, “Tissue shape and deformation versus pressure as a characterization of the seating interface,” Assist Technol., vol. 2, pp. 93-99, 1990

[11] K. Bogie, S. Reger, S. Levine, V. Sahgal, “Electrical stimulation for pressure sore prevention and wound healing,” Assist Technol., vol. 12, pp. 50-66, 2000

[12] K. Bogie, R. Triolo. “Effects of regular use of neuromuscular electrical stimulation on tissue health,” J Rehabil Res Dev.. vol. 40, pp. 469-476, 2003

[13] K. Bogie, X. Wang, R. Triolo, “Long-term prevention of pressure ulcers in high-risk patient: A single case study of the use of gluteal neuromuscular electric stimulation,” Phys. Med. Rehabil., vol. 87, pp. 585-591, 2006

[14] C. Oomens, O. Bressers, E. Bosboom, C. Bouten, D. Blader, “Can loaded interface characteristics influence strain distributions in muscle adjacent to bony prominences?,” Comput. Method Biomech. Biomed. Engin., vol. 6, pp. 171-180, 2003

[15] E. Linder-Ganz, A. Gefen, “Mechanical compression-induced pressure sores in rat hindlimb: muscle stiffness, histology, and computational models,” J. Appl. Physiol., vol. 96, pp. 2034-2049, 2004

[16] A. Palevski, I. Glaich, S. Portnoy, E. Linder-Ganz, A. Gefen, Stress relaxation of porcine gluteus muscle subjected to sudden transverse deformation as related to pressure sore modeling, J Biomech Eng., vol. 128, pp. 782-787, 2006

[17] E. Linder-Ganz, N. Shabshin, Y. Itzchak, Z. Yizhar, I. Siev-Ner, A. Gefen, “Strains and stresses in sub-dermal tissues of the buttocks are greater in paraplegics than in healthy during sitting,” J Biomech., vol. 41, pp. 567-580, 2007

[18] E. Linder-Ganz, N. Shabshin, Y. Itzchak, A. Gefen, “Assesment of mechanical conditions in sub-dermal tissues during sitting: a combined experimental-MRI and finite element approach, J Biomech., vol. 40, pp. 1443-1454, 2007

[19] E. Linder-Ganz, A. Gefen, “Stress analyses coupled with damage laws to determine biomechnical risk factors for deep tissue injury during sitting,” J Biomech Eng., to be published

[20] B. Todd, J. Thacker, “Three-dimensional computer model of the human buttock, in vivo,” J. Rehabil. Res. Dev., vol. 31, pp. 111-119, 1994