

# Finite Element Analysis of Contact Pressures between Seat Cushion and Human Buttock-Thigh Tissue

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## Abstract

Unrelieved pressure on load-bearing muscle tissues of humans can produce pressure ulcers. In a seated upright posture, the highest pressures occur inferior to the ischial tuberosities (ITs). Moreover, the vibration can initiate the development of pressure ulcer. Therefore, the seat cushion is not only used to lower the maximum seating pressure on buttocks but also minimize the transmission of vibration to human body. The purpose of this study was to investigate the effects of varying vertical vibration frequencies on seat-interface contact pressure during sitting on three different seat cushions by using a finite element modeling approach. A simplified two-dimensional human buttock-thigh model was developed to simulate the mechanical response of the muscle of buttocks and thigh under vertical vibration. Static and vibrational loads with five different frequencies of 0.1, 1, 10, 30 and 50 Hz and the same amplitude of 3 mm were applied to different seat cushions. The result showed that the “SAF 6060” seat cushion with both hyperelastic and viscoelastic behaviors could be effective in reducing the amplitude of varying maximum contact pressure, especially for the frequency of 10-20 Hz. This method could help in design of seat cushions with appropriate material properties and shape so as to reduce vibrations transmitted to human body at a certain frequency range.

**Keywords:** Finite Element Analysis, Seat Cushion, Vibration, Buttock-Thigh

## 1. Introduction

Static seating comfort is important for drivers and wheelchair users. Seat-interface pressure distribution has been used as an objective measure for discomfort prediction [1]. Experimental methods could find the interface pressure between human body and seat. However, it could not provide the information about subcutaneous stress and deformations of soft tissues. For drivers and wheelchair users who have sat for a long time, they could be associated with an increased risk of pressure ulcers [2]. Moreover, severe pressure ulcer initiates in muscle tissue overlying a bony prominence (ischial tuberosity) and progresses outwards through fat and skin, giving rise to the subcutaneous stress [3,4]. Many researchers conducted two-dimensional (2D) and three-dimensional (3D) finite element analyses to investigate the subcutaneous stress [1,5-12]. Ragan *et al.* determined the effects of the thickness of polymer foam wheelchair cushions on subcutaneous pressures during seating by using a finite element approach [8]. It was found that seat-interface pres-

sures were a good indicator for reducing the subcutaneous stress.

Shocks normal to the seat cushions and shear stresses could initiate the development of pressure ulcer [13,14]. Following the directive 2002/44/EC of the European Parliament, manufacturers of seat cushions were required to limit vibration exposure to users. Wu *et al.*, [15] found that the maximum ischium pressure and the effective contact area on a soft seat occur near resonant frequency of the coupled human-seated system (2.5-3.0 Hz), and generally increased considerably with increase in the magnitude of vibration excitation. DiGiovine *et al.*, [16] discussed that the application of the appropriate seating system may reduce the amount of whole-body vibration experienced by an individual during manual wheelchair propulsion. They also suggested the manufacturers should concentrate on designing seat cushions that shift the resonant frequency away from the range of frequencies most sensitive to humans during whole-body vibration (4-12.5 Hz) as defined in ISO 2631-1:1997 [17].

Owing to these reasons, many researchers developed a

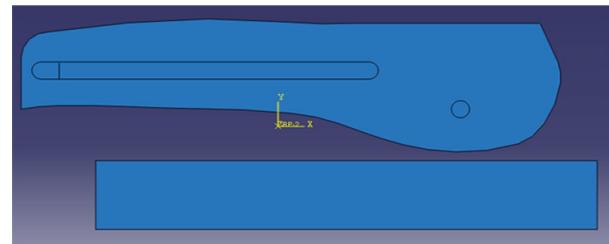
biomechanical model of human body for investigating the dynamic response to vertical vibrations. Verver *et al.*, [18] developed a finite element model for the human body using MADYMO while Siefert *et al.* [9] used CASIMIR for model creation. However, for their models, only hyperelastic behavior was used to describe the seat cushion and human soft tissue but their viscoelastic properties were not considered. Kitazaki and Griffin [19] used beam, spring and mass elements to model a 2D human model including the spine, viscera, head, pelvis and buttocks tissue. This model was good for estimating the transmission capability from vertical seat motion to vertical spinal motion. Other methods such as lumped parameter model [20,21] and finite segment model [22] were also used to evaluate the whole-body vibration. However, these two methods could not present realistic human geometry. Other researchers experimentally determined if seat cushions of a selected wheelchair could minimize the transmission of vibrations to users [16,23, 24].

The main goal of our study was to investigate the effects of vertical vibration on subcutaneous stress of buttocks sitting on three different seat cushions by using a finite element modeling approach. The simplified buttock-thigh model was developed for the analysis. The hyperelastic and viscoelastic properties were used to describe the mechanical behaviors of the human soft tissue and seat cushion.

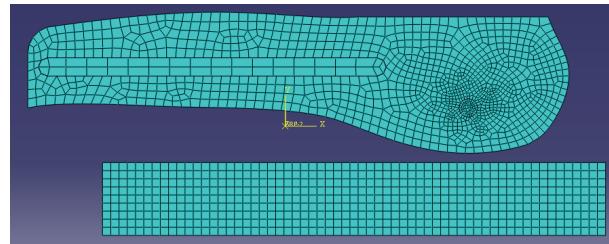
## 2. Methodology

### 2.1. Buttock-Thigh Model

**Figure 1** shows the buttock-thigh model consisting of a femur and ischial tuberosity (IT) for representing humans in a sitting posture. It was assumed that a human sit uprightly on the cushion and there was no support on the feet. The total length of the buttock-thigh model was 60 cm for the male at the fifty-percentile [25]. A circle with a radius of 1cm represents the cross section of the IT where supports the body's weight in a sitting position. The distance between the bottom of the IT and the skin was 4 cm [8]. The thickness of the cushion was set to 8 cm because Chow and Odell [26] found that the cushion thickness beyond 8cm was ineffective in further reducing subcutaneous stress. The distance between the buttock-thigh model and the cushion was set to 1 cm at the beginning step because the buttocks were assumed not to sit on the cushion initially. With the finite element tool – ABAQUS, the buttock-thigh model and seat cushion were meshed using 2D plane strain elements as shown in **Figure 2**.



**Figure 1. The buttock-thigh model and the cushion.**



**Figure 2. Finite element model of the buttock-thigh model and the cushion.**

### 2.2. Material Models

The muscle and seat cushions were assigned different material properties. All bones in the model were defined as rigid bodies, because their stiffness is very high as compared to the muscle and cushion.

#### 2.2.1. Seat Cushions

Three different material properties of seat cushions were considered in this study. One of the seat cushions was assumed to be made of SAF 6060 polymer foam with rate-independent hyperelastic and viscoelastic behaviors, which was produced by Foam Partner Fritz Nauer AG. Another two seat cushions were similar to the above-mentioned SAF6060 cushion but with a linear elastic response instead of the hyperelastic behavior. The Young moduli of these two cushions were separately set to 15 kPa (Elastic 15000) and 20 kPa (Elastic 20000), while their Poisson's ratio was 0.3 [27].

The hyperealistic behavior of the seat cushion SAF6060 was represented using a non-linear isotropic compressible hyperelastic soft foam material model or a so-called hyperfoam. The hyperelastic behavior of the foam material is described by the strain energy potential,  $U$  in the following form:

$$U = \sum_{i=1}^N \frac{2\mu_i}{\alpha_i^2} \left[ \hat{\lambda}_1^{\alpha_i} + \hat{\lambda}_2^{\alpha_i} + \hat{\lambda}_3^{\alpha_i} - 3 + \frac{1}{\beta_i} \left( (J^{el})^{-\alpha_i \beta_i} - 1 \right) \right] \quad (1)$$

where  $N$  is the order of the strain energy potential,  $\mu_i$ ,  $\alpha_i$  and  $\beta_i$  are the temperature-dependent material parameters;  $\hat{\lambda}_i = (J^{th})^{-\frac{1}{3}} \lambda_i$ ,  $\hat{\lambda}_1 \hat{\lambda}_2 \hat{\lambda}_3 = J^{el}$  and  $\lambda_i$  are the principal stretches.  $J^{el}$  is the ratio of elastic-deformation to

volume-change and  $J^h$  is the ratio of the thermal-strain to volume-change. The coefficients  $\mu_i$  are related to the initial shear modulus while the coefficient  $\beta_i$  determines the degree of compressibility and is related to the Poisson's ratio [28]. In the present work, polyurethane soft foam parameters determined by Schrodt *et al.* [29] from uniaxial compression tests were used to define the above-mentioned material parameters for SAF 6060 cushion as listed in **Table 1**. Moreover, its density was set to  $60 \text{ kg/m}^3$  and a second order ( $N = 2$ ) of the strain energy potential was used.

The viscoelastic behavior of the SAF 6060 cushion was defined by using a time-based Prony-series model for the shear modulus only because the time-dependency of bulk modulus is generally not significant [5]. Time-dependent shear relaxation modulus  $G(t)$  is given by

$$G(t) = G_0 - \sum_{i=1}^N G_i \left(1 - e^{-t/\tau_i^G}\right) \quad (2)$$

where  $\tau_i^G$  is the relaxation time and  $N$  is the order of the Prony series.  $G_0$  and  $G_i$  are the instantaneous shear modulus and relative shear modulus, respectively. With reference to the findings by the work of Grujicic *et al.* [5], the viscoelastic material parameters for the SAF 6060 cushion were defined such that  $N = 2$ ,  $G_1 = 0.3003$  and  $\tau_1 = 0.010014 \text{ s}$ , and  $G_2 = 0.1997$  and  $\tau_2 = 0.1002 \text{ s}$ .

### 2.2.2. Muscle

The muscular portion of the buttock-thigh model was modeled using a non-linear visco-hyperelastic isotropic material model to describe the human soft tissue. The density of soft tissue is  $1000 \text{ kg/m}^3$  [30] and hyperelastic portion of the soft tissue is expressed in the form of the polynomial strain energy potential,  $W$ :

$$W = \sum_{i+j=1}^N C_{ij} (\bar{\ell}_1 - 3)^i (\bar{\ell}_2 - 3)^j + \sum_{i=1}^N \frac{1}{D_i} (J^{el} - 1)^{2i} \quad (3)$$

where  $C_{ij}$  and  $D_i$  are the material parameters. A higher  $N$  value may provide a better fit to the exact solution. However, it may cause numerical difficulty in fitting the material constants and require enough data to cover the entire range of interest of deformation. Therefore a very higher  $N$  value is not usually recommended. In the present study,  $N = 2$  was chosen and the hyperelastic parameters for the muscle model obtained from a URL, <http://lyle.smu.edu/~hyao/academics.html#Research> are listed in **Table 2**. Referring to the work of Tang and Tsui [31], the viscoelastic parameters for the muscle model were set as  $G_1 = 0.5$ ,  $K_1 = 0.5$  and  $\tau_1 = 0.8 \text{ s}$ .

### 2.3. Simulation Set-Up

In the present study, ABAQUS explicit dynamics analysis has been performed to deal with the dynamic problem.

As this type of analysis uses a consistent large-deformation theory, the cushion and the muscle model could undergo large rotations and deformation. The analysis procedure was implemented by using an explicit integration rule and diagonal element mass matrices. The equations of motion for the body were integrated using the following explicit central-difference integration rule:

$$\dot{u}_{(i+\frac{1}{2})}^N = \dot{u}_{(i-\frac{1}{2})}^N + \frac{\Delta t_{(i+1)} + \Delta t_i}{2} \ddot{u}_{(i)}^N$$

and

$$u_{(i+\frac{1}{2})}^N = u_{(i)}^N + \Delta t_{(i+1)} \dot{u}_{(i+\frac{1}{2})}^N$$

where  $u^N$  is a degree of freedom (a displacement or rotation component) and the subscript  $i$  refers to the increment number in an explicit dynamics step. The central-difference integration operator is explicit such that the kinematic state is advanced using known values of  $\dot{u}_{(i+1/2)}^N$  and  $\ddot{u}_{(i)}^N$  from the previous increment [28].

### 2.4. Interaction between the Buttock-Thigh Model and Cushion

In this work, it was assumed that the human sit on the cushion and then the vertical vibration was applied onto the bottom of the cushion. The loading was applied to the model due to the weight of the human, such that a gravity-based body force was used to prescribe the loading. The interaction between the buttock-thigh model and the cushion was analyzed in ABAQUS/Explicit using a penalty contact method with finite-sliding. Surface-to-surface contact with a coefficient of friction of 0.5 [5] was used to define the contact pair between the buttock-thigh model and cushion. The outer surface of the buttock-thigh model was defined as the "master surface" which has a larger surface and higher stiffness, while the surface of the cushion was defined as the "slave surface" which is softer and has smaller surface than that of the buttock-thigh model. The surfaces between the bone and muscle were tied together so that there was no relative motion between them.

**Table 1. Hyperelastic material parameters for the SAF6060 cushion.**

| $\mu_1$ [MPa]          | $\alpha_1$          | $\beta_1$              | $\mu_2$ [MPa]         | $\alpha_2$          | $\beta_2$             |
|------------------------|---------------------|------------------------|-----------------------|---------------------|-----------------------|
| $0.481 \times 10^{-2}$ | $0.198 \times 10^2$ | $0.145 \times 10^{-1}$ | $0.36 \times 10^{-2}$ | $0.198 \times 10^2$ | $0.65 \times 10^{-2}$ |

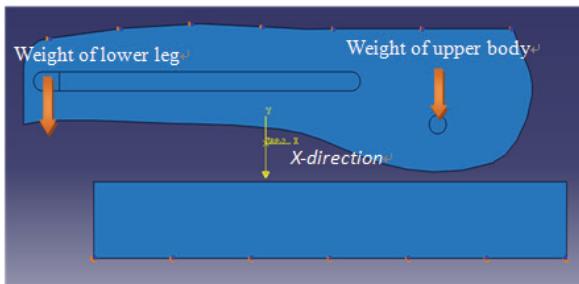
**Table 2. Hyperelastic material parameters for the muscle model (All values in MPa).**

| $C_{10}$ | $C_{01}$ | $C_{20}$ | $C_{11}$ | $C_{02}$ | $D_1$   | $D_2$ |
|----------|----------|----------|----------|----------|---------|-------|
| 0.08556  | -0.05841 | 0.039    | -0.02319 | 0.00851  | 3.65273 | 0     |

## 2.5. Loading and Boundary Conditions

According to fifty-percentile male body segment masses [25], the total weight is 80.4 kg, including 54.5 kg of the upper body and 25.9 kg of the lower body. The current model represented only one side of the body so that the mass assigned to the model should be halved. Thus, the weight of the upper body on the ischial tuberosity was set as 27.3 kg while the weight of lower leg on the femur was set as 4.5 kg. **Figure 3** shows the positions of the assigned masses. It was assumed that the cushion was placed on a rigid surface so that the bottom surface of the cushion was restricted to move in all directions. Moreover, the upper surface of the buttock-thigh model was limited to move in *X*-direction only.

The analyses were performed in two steps. In the first step, the buttock-thigh model moved to sit on the seat cushion due to the gravity load ( $9.81 \text{ ms}^{-2}$ ). After 15 seconds, there followed a second step in which a vertical vibration in the form of harmonic motion was applied onto the bottom of the cushion. The periodic definition method was used to define the amplitude. The frequencies of the vibration were chosen to be 0.1, 1, 10, 20 and 50 Hz which are the frequencies generated mostly in our life according to **Table 3** [32]. A vibration amplitude of 3 mm was applied to the bottom of the cushion. Each vibration case was conducted for 50 cycles (see **Table 4**).



**Figure 3. Loading and boundary conditions on the buttock-thigh model and cushion.**

**Table 3. Sensitivity of human systems to vibration.**

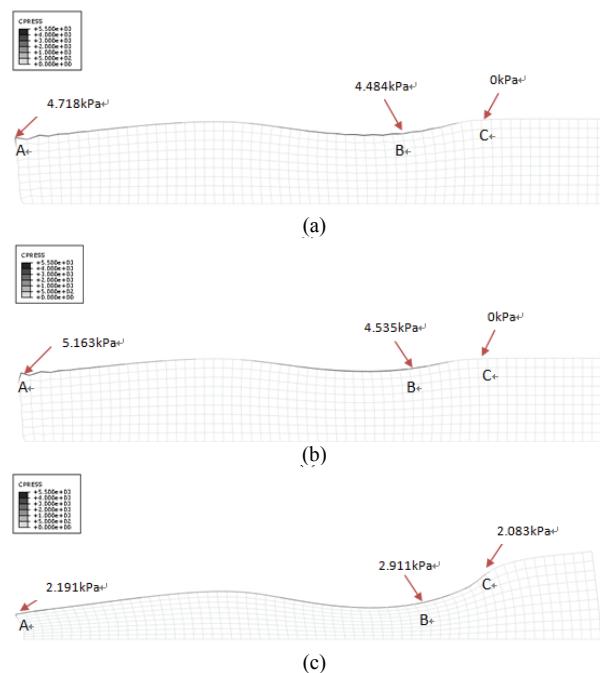
| Frequency Level | Frequency range | Sensitivity                                      | Vibration Generator      |
|-----------------|-----------------|--|--------------------------|
| Low             | 0 to 1-2 Hz     | Vestibular system                                | Ships, cranes, aircrafts |
| Middle          | 2 to 20-30 Hz   | Biomechanics: body resonances                    | Vehicles, aircrafts      |
| High            | > 20 Hz         | Somesthetic receptors in muscles, tendons, skins | Tools, machinery         |

**Table 4. Different loading conditions for the simulation.**

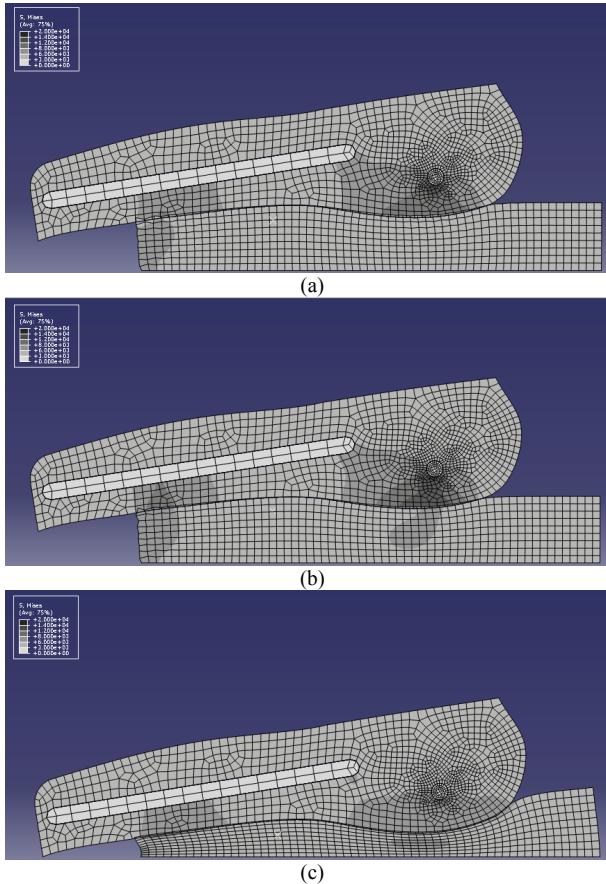
| Duration (Second) | Loading  |                              |                            |                             |                             |                             |
|-------------------|----------|------------------------------|----------------------------|-----------------------------|-----------------------------|-----------------------------|
|                   | Grav ity | Vertical vibration of 0.1 Hz | Vertical vibration of 1 Hz | Vertical vibration of 10 Hz | Vertical vibration of 20 Hz | Vertical vibration of 50 Hz |
| 15                | 500      | 50                           | 5                          | 2.5                         | 1                           |                             |

## 3. Results and Discussions

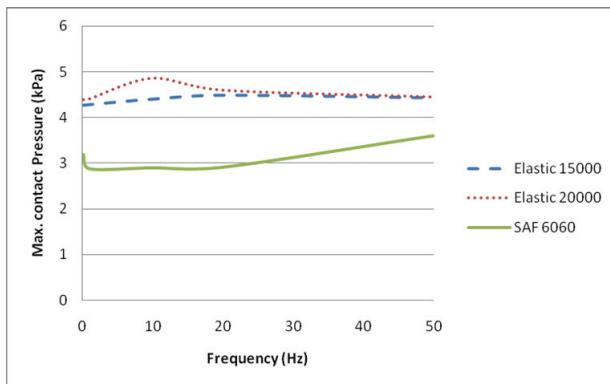
As the distribution of the contact pressure at the seated human/cushion contact interface is important for determining the seating comfort [5], the maximum contact pressure at three different locations of the three cushions at the frequency of 20 Hz have been identified as shown in **Figure 4**. Among them, the SAF 6060 cushion shows the lowest contact pressure at the locations of A and B. As the location B is under the ichial tuberosities (IT), minimizing the contact pressure at this location means minimizing the stress under IT. It can also be observed from **Figure 5** that the maximum von Mises stress near IT using the SAF 6060 cushion is lower than the other two cushions by about 30~37% at the same frequency of 20 Hz. Moreover, the SAF 6060 cushion shows lower stress within the buttock especially at the region near the cushion as shown in **Figure 6**. Therefore, the SAF 6060 cushion is effective in reducing the stress below IT, and also has better pressure distributions at three distinct locations than the other two.



**Figure 4. Maximum contact pressure at the three different locations of the three cushions at the frequency of 20 Hz. (a) Elastic 15000; (b) Elastic 20000 and (c) SAF 6060.**



**Figure 5. von Mises stresses distribution within the human body and cushion at the frequency of 20 Hz. (a) Elastic 15000; (b) Elastic 20000 and (c) SAF 6060.**



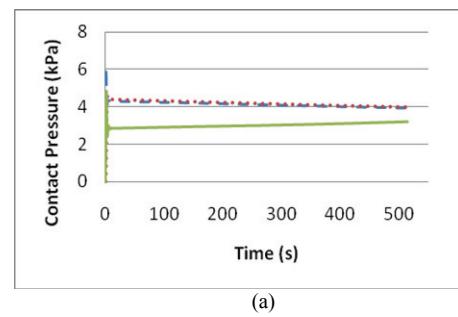
**Figure 6. Maximum contact pressure versus frequency.**

For a range of frequencies under study, the magnitude of maximum contact pressure in the SAF 6060 cushion is much lower than that of the other two cushions as shown in **Figure 6**. **Figure 7** shows the variation of maximum contact pressure with time for the three different cushions in response to five different frequencies. In **Figure 7**, the contact pressure generally increases rapidly to reach a maximum for all frequencies and cushions during the

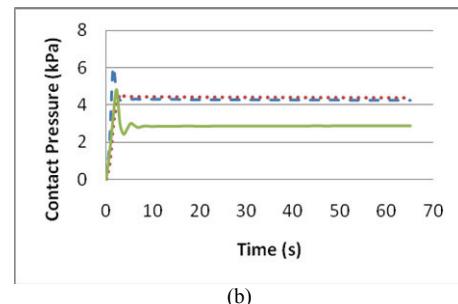
first step, because the buttock-thigh model fell quickly onto the cushion due to the gravity.

During the second step, all the three cushions were subjected to a vertical vibration of different frequencies. At the frequency of 0.1 Hz, the responses of all three cushions are slow and do not vary sinusoidally after 15 seconds as shown in **Figure 7(a)**. It can be observed from **Figure 7(a)** that the maximum contact pressure at the location B for the Elastic 15000 and Elastic 20000 cushions keep increasing with time while that for the SAF 6060 cushion increases with time up to 500 seconds. When the frequency is increased to 1 Hz, there is only a slight change in the maximum contact pressure around 0.02 to 0.04 kPa as shown in **Figure 7(b)**. When the frequency is increased to 10 Hz or above, the responses of all the cushions become significant after 15 seconds. It is apparent from **Figures 7(c)** and **7(d)** that the amplitude of varying maximum contact pressure for the SAF 6060 cushion at the frequency of 10 Hz and 20 Hz is only around 0.15 kPa, which is much lower than those of the other two cushions by 63~85%. At the frequency of 50 Hz, the amplitude for the SAF 6060 cushion has sharply increased to 1.2 kPa, which is much higher than those of the other two cushions as shown in **Figure 7(e)**. Therefore, the SAF 6060 cushion is effective in reducing the amplitude of varying maximum contact pressure, especially for the frequency of 10~20 Hz, which belong to the frequency range of vibration generated mostly by vehicles and aircrafts.

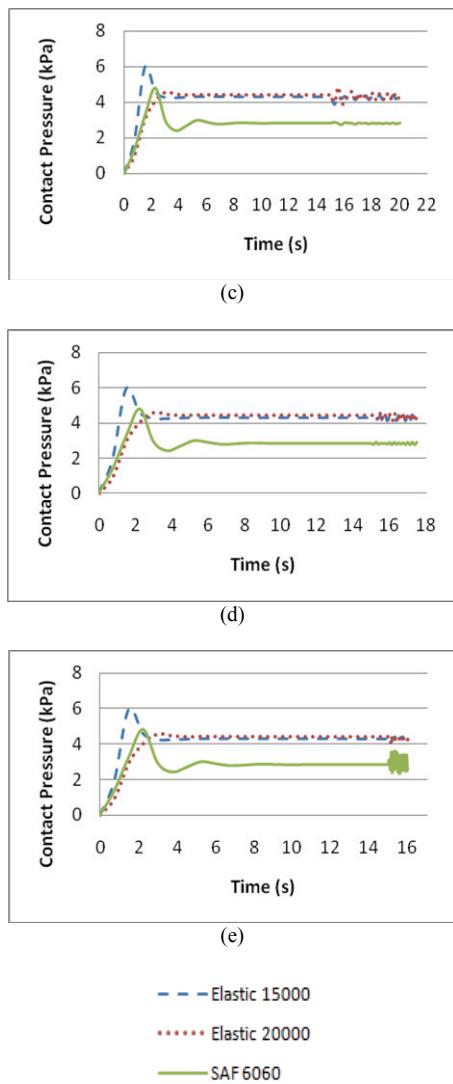
For simplification and reducing the amount of CPU time for running the simulation, the 2D model of the buttock-thigh was firstly developed to study mechanical responses in bony prominence of IT and the vibration



(a)



(b)



**Figure 7. Variation of maximum contact pressure at location B with time at various frequencies. (a) 0.1 Hz; (b) 1 Hz; (c) 10 Hz; (d) 20 Hz and (e) 50 Hz.**

transmissibility of different cushions under vertical vibration at different frequencies. As 3D finite element model has the advantages of an accurate anatomical geometry and accuracy in performance, a 3D model representing more complicated geometry may be developed in future work.

#### 4. Conclusions

This simplified simulation was designed to mimic the response of the human under the vertical vibration. Finite element analysis could evaluate the transmission of vibrations onto different seat cushions subjected to varying frequencies. From this analysis, the SAF 6060 seat cushion was found to be effective in reducing the amplitude of varying maximum contact pressure, especially for the

frequency of 10-20 Hz, belonging to the frequency range of vibration generated mostly by vehicles and aircraft. Thus, this method is useful for designing the material properties and the shape of the seat cushion for reducing the transmission of vibrations to users at a certain frequency range.

#### 5. Acknowledgements

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