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SPECIAL ISSUE

Evaluation of a new sitting concept designed for prevention of pressure ulcer on the buttock using finite element analysis

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Abstract Excessive compressive load induces pressure related soft tissue damage, i.e. pressure ulcer (PU), in buttock area in wheelchair users. In solving this problem, our previous study has introduced a concept of *Off-Loading* sitting, which partially removes the ischial support to reduce pressure under buttocks. However, the effect of this sitting concept has only been evaluated using the interface pressure and tissue perfusion measurements. The objective of this investigation was to evaluate the *Off-Loading* posture for its ability to reduce internal pressure and stress in deep buttock tissues. This evaluation was performed on a 3D finite element (FE) model which was established and validated in a sitting posture and has realistic material properties and boundary conditions. FE analysis in this study confirmed that the pressure relief provided by *Off-Loading* posture created profound effect in reducing the mechanical stress within deep tissues. It was concluded that *Off-Loading* posture may prove beneficial in preventing sitting related PU.

Keywords Finite element analysis · Pressure ulcer · New sitting concept · Buttock thigh · Wheelchair

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1 Introduction

It is estimated that up to 33.6% of spinal cord injured (SCI) patients have serious tissue breakdown, i.e. pressure ulcer (PU) [17], at pressure areas due to excessive pressure in prolonged sitting [1, 2, 9, 19]. PUs involving sub-dermal tissue damage, where damage originates in muscle tissue, were recently termed "deep tissue injury" by the US National Pressure Ulcer Advisory Panel [1], and are attracting growing attention from the medical community. This fact asserts that the responses in deep tissues, in addition to the interface pressure on the buttocks, should be evaluated in studies related to PUs.

Some studies suggested a need to establish the associations between external mechanical loads and the internal local mechanical condition of the tissue [6, 7]. It is pointed out that the interface pressure measurements provide only a very small portion of the information to the overall problem [19] and help little for understanding the situation in deep tissues [4]. Finite Element (FE) analysis is a powerful engineering tool to simulate stress–strain condition within complicated structures; therefore, it can be used to predict mechanical responses in deep buttock tissues under the sitting load. In this sense, the FE method may help establish criteria for assessing seating systems in the ability of achieving optimal pressure relief in the deep tissue for preventing sitting related PUs.

Our previous study [16] has introduced a new sitting concept, *Off-Loading* posture, for wheelchair users in the attempt to reduce pressure under ischia (Fig. 1). It was confirmed that this *Off-Loading* concept, by lowering down the back portion of the seat pan (Fig. 1), significantly reduced interface pressure on the buttocks. This finding was, however, only on the superficial pressure mapping, which did not provide clues of mechanical responses within the deep tissue such as in fat and muscle. Since it is likely that different tissues have different susceptibility to damage under mechanical compression [19], it is necessary to investigate whether the *Off-Loading* posture can benefit deep tissues.

The hypothesis of the study was that the pressure relief provided by partially removing the ischial support, i.e. using the *Off-Loading* posture, will have profound effect in reducing the mechanical stress within deep soft tissues. The objective of this investigation was, therefore, to evaluate the *Off-Loading* concept using a 3D FE model which has been developed and validated in our previous study [12, 15]. It was expected that the FE analysis may help predict reliably how the skin, fat and muscle in the buttock-thigh region mechanically respond differently to the sitting load, as compared with a regular sitting posture.

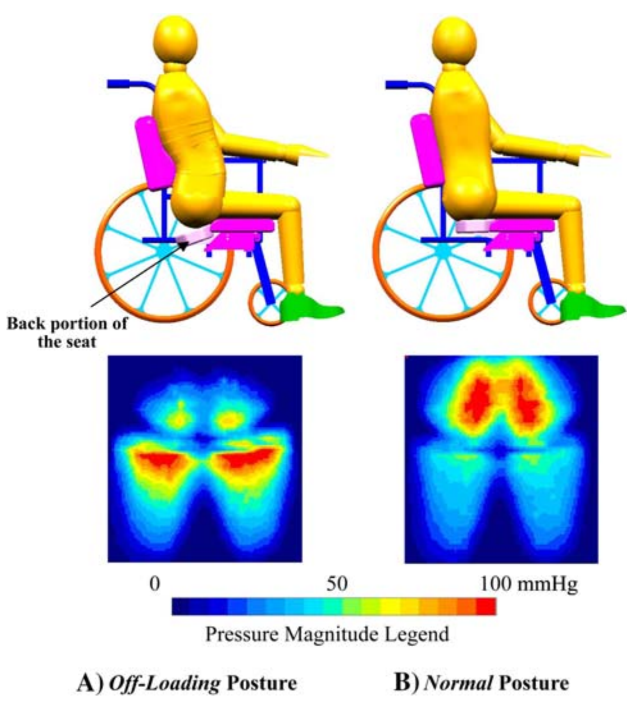

Fig. 1 A new sitting configuration, *Off-Loading* posture (**a**) is illustrated in comparison with a regular (*Normal* posture) sitting posture (**b**). The *Off-Loading* posture was achieved by tilting a movable back portion of seat downward with respect to the fixed fontal portion of seat. Below each of the sitting configurations, the corresponding average interface pressure map (mm Hg) from 35 participants is given

2 Materials and methods

2.1 FE model development and validation

In our previous study, a 3D FE model [15] was created based on the buttock-thigh structure reconstructed from MRI images obtained in a simulated sitting posture (Fig. 2a right). The established model was validated quantitatively for evaluating internal stress–strain condition within buttock structure in a sitting posture.

2.2 Sitting postures

Figure 1 shows the two sitting postures, a *Normal* posture and an *Off-Loading* posture, which were evaluated in this study using the established FE model. A *Normal* posture was described as sitting upright on a flat seat and with a flat

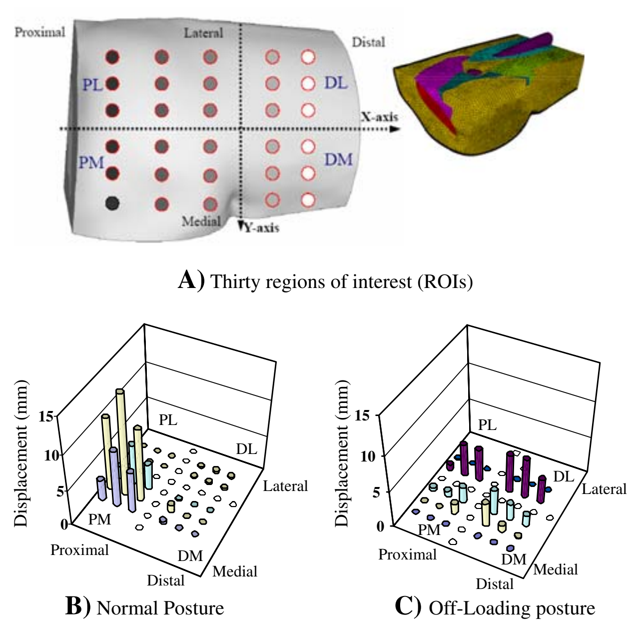

Fig. 2 **a** The Cartesian coordinate system used in the study. Thirty regions of interest (ROIs) were identified over the skin of the sitting area. The buttock-thigh area was divided into four regions, the distal–medial (DM), distal–lateral (DL), proximal–medial (PM) and proximal–lateral (PL) regions. Gross displacement in posterior–anterior direction from 30 ROIs distributed in regions of DL, PL, DM and PM for the *Normal* Sitting posture (**b**), and the *Off-Loading* posture (**c**)

backrest, while an *Off-Loading* posture was sitting upright on a seat with partially removed ischial support, and with an enhanced lumber support at the level of L4 (Fig. 1).

2.3 FE model input

Thirty-five individuals (41.3 ± 12.1 years; 72.1 ± 12.6 kg; 168.0 ± 8.5 cm) with no history of neuromuscular disorders were used to obtain the actual interface pressure distribution between the seat cushion and the buttock-thigh. Recordings were obtained when the subjects sat in the *Normal* and *Off-Loading* postures. For each of the postures, the obtained interface pressure data were averaged across the participants. Then the averaged interface pressure data for the *Normal* and *Off-Loading* postures were each applied to the FE model to simulate these two sitting conditions. The FE analysis was then run on an ABAQUS/Standard 6.5 (ABAQUS, INC., Pawtucket, RI) platform.

2.4 Evaluating the effects of Off-Loading posture using the FE model prediction:

2.4.1 Gross displacement of soft tissues under the sitting pressure in Normal and Off-Loading postures

It was assumed that the bony structure remained static when loaded. A Cartesian coordinate system was defined based on the femur-pelvis bony structure. This coordinate system took the origin at the center of the femoral head. The *X*-axis was pointing to the distal along the femoral shaft. The *Y*- and *Z*-axes were pointing to the medial and the superior, respectively (Fig. 2a). Thirty regions of interest (ROIs) were identified over the skin of the sitting area (Fig. 2a). On each image, vectors pointing from the origin of the coordinate system to the specific locations on the skin were constructed to compute the gross displacement. In order to compare the differences of the gross displacement in different portions of the buttock, four regions, the distal–medial (DM), distal–lateral (DL), proximal–medial (PM) and proximal–lateral (PL) regions, were defined (Fig. 2a). The sitting induced changes of the coordinates of the FE nodes in these ROIs were taken as the FE predicted gross displacement.

2.4.2 Compressive strain of muscle under the sitting pressure load in Normal and Off-Loading postures

Three sagittal MRI slices of the buttock-thigh model were used to calculate the compressive strain of the muscle layer. Each sagittal slice had a thickness of 5 mm. The central piece of the three slices had its medial–lateral center at the tip of the ischial tuberosity. In this way, these three slices covered the portion of the buttock-thigh from 7.5 mm medial to the ischial tuberosity to 7.5 mm lateral to it. On each slice, 14 nodes were selected for the muscle layer from proximal to distal. There were eight nodes on buttock distributing from proximal (two nodes), ischial tuberosity (four nodes) and then to the distal region (two nodes) of the buttock. Six nodes were on thigh evenly distributing among proximal, central, and the distal regions. Then the gross deformation of the muscle layer was obtained using the changes in the anterior–posterior coordinate of these nodes. The compressive strain was the percentage of such deformation relative to the initial thickness. For each region, the strain values were averaged across the nodes contained in this region and then across the three slices. This calculation was done for both the *Normal* and *Off-Loading* postures.

2.4.3 Internal von Mises stress and compressive stress distribution within the buttock-thigh soft tissues

The internal compressive stress and von Mises stress distributions were calculated for the muscle, fat and skin for the entire region of the buttock-thigh.

For all the experiments involving human subjects, a written informed consent was obtained for each participant following the guidelines of the Institutional Review Board of the performance site.

3 Results

Interface pressure. In Fig. 1, average interface pressure (mm Hg) on the seat is shown for the 35 subjects. In the *Normal* posture, the interface pressure was concentrated within the vicinity of ischial tuberosities, with the thighs taking substantially less interface pressure. In the *Off-Loading* posture, the concentrated interface pressure at ischial tuberosities was mostly shifted towards the thighs, and the middle part of the thighs took most of the loads.

Displacement on skin of the buttock-thigh. Figure 2b, c showed gross displacement of the soft tissue predicted by FE model for both the *Normal* and *Off-Loading*. In *Normal* posture, large displacement was seen concentrated in all ROIs in the PM region (Mean ± SD; 7.0 ± 4.1 mm; range of 1.8–14.2 mm), with the largest value as 14.2 mm in the vicinity of ischial tuberosity. At the same time, soft tissue displacement was close to zero (–1.0 ± 0.6 mm; range of –1.8–1.1 mm) in the other three regions. In *Off-Loading* posture, the displacement on skin was within the range of –1.4–5.5 mm for all 4 regions. The largest displacements were in DL (–1.4–5.5 mm) and DM (–1.0–3.5 mm) regions. Compared with the displacement pattern in *Normal* posture, the place where the soft tissue experienced large displacement was seen moved from the area under ischial tuberosity (with a max value of 14.2 mm) to the thigh (with a max value of 5.5 mm) with a reduction of magnitude. An average reduction of soft tissue displacement as 6.5 ± 4.4 mm for PM region (buttock area under the ischial tuberosity) and an average increase of 1.0 ± 1.5 mm for DM region (thigh) were predicted in comparison with those in *Normal* posture.

Compressive strain on muscles. The change pattern of the compressive strain on the muscle induced by *Off-Loading* posture was in general comparable with that of the displacement for the entire buttock-thigh structure. The compressive strain on the muscle closer to the IT was decreased from 6.9 ± 0.7% (N = 3) in *Normal* posture to 0.3 ± 1.3% (N = 3) for the *Off-Loading* posture (Fig. 3). On the other hand, the compressive strain on the center of the thigh region was increased from 0.2 ± 0.0% in *Normal* posture to 1.1 ± 0.6% in *Off-Loading* posture (Fig. 3).

Compressive stress and von mises stress distribution. The predicted compressive stress and von Mises stress distributions for the entire buttock-thigh structure are shown in Fig. 4. It was seen that, in *Normal* posture, the high-pressure and stress region was at the location immediately beneath the bony prominence of ischial tuberosity. However, this high-stress region was relocated to the thighs with a reduction of magnitude in the *Off-Loading* posture (Fig. 4).

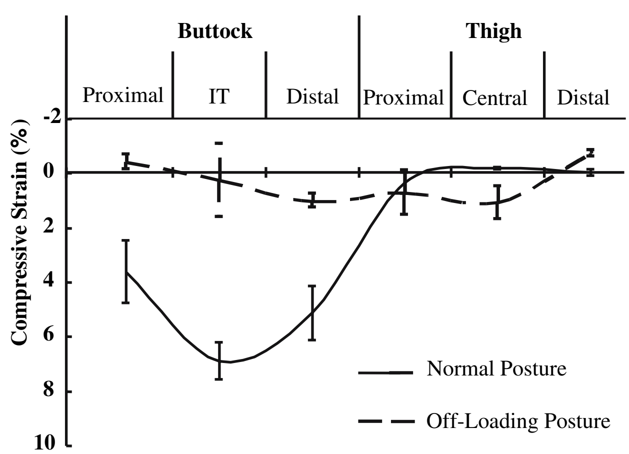

Fig. 3 Anterior–posterior compressive strain (%) of the muscle layer in sagittal plane in a portion covered 15 mm thickness buttock-thigh from 7.5 mm medial to the ischial tuberosity to 7.5 mm lateral to it. The larger compressive strain (%) in the *Normal* sitting posture, which was seen underneath the ischial tuberosity, was shifted toward the thigh with a largely decreased compressive strain (%) in the *Off-Loading* posture

4 Discussions and conclusions

This study was performed to evaluate a specific sitting posture, the *Off-Loading* posture, using a validated comprehensive 3D FE buttock-thigh model which takes into consideration the actual sitting joint configuration and realistic boundary conditions. The current study confirms our hypothesis that the pressure relief provided by the *Off-Loading* posture has profound effect in decreasing the stress within the deep tissues of the buttocks. Our findings show that at the same time of releasing interface pressure, the *Off-Loading* posture significantly redistributed the internal compressive stress and von Mises stress within the deep tissues of the buttocks. It was found that, in the *Off-Loading* posture, the internal compressive stress which was highly concentrated in the deep tissues at the location of the ischial tuberosity in *Normal* sitting posture were repositioned to the thigh with a substantially decreased magnitude.

The most common sites for sitting related PUs are areas close to a bony prominence. At these locations, such as the ischial tuberosity, tissue necrosis was frequently seen starting from deep in the tissues and progresses towards the superficial to become an open wound [1]. Therefore, there is a need for a tool, which can estimate the internal mechanical responses in the deep tissues, such as stress and strain, to external sitting load, to provide, from a mechanical point of view, a deep insight into the relationship between the formation of deep tissue damage and the interface pressure. With this understanding, it is possible to establish a criterion for evaluating designs of new sitting systems which aim at achieving optimal pressure relief in the sitting area for wheelchair users. The results in the current study proved that the *Off-Loading* posture is effective in reducing the risk of PUs by decreasing large compressive strain, high internal compressive stress in the deep tissue overlying the ischial tuberosity.

It has been suggested that the muscular layer is the most *vulnerable* to pressure induced tissue damage due to its high metabolic rate and the dependence on tissue perfusion [8, 18]. This vulnerability puts muscle tissue in a highly susceptible situation to localized compression, eventually leading to tissue degeneration in the form of a deep pressure injury. Therefore, our findings about the concentrated stress in the deep layer of the muscle tissue is evidence for mechanism of this kind of deep tissue injury.

There have been several attempts in using FE analysis to evaluate sitting induced mechanical response in deep tissue of the buttocks [5–7, 11, 19, 23, 24]. Chow and Odell (1978) [6], using a simple axi-symmetric buttock FE model, found that the buttock tissue experienced small deformation when using a floating support design cushion. Dabnichki et al. (1994) [7], employing contact

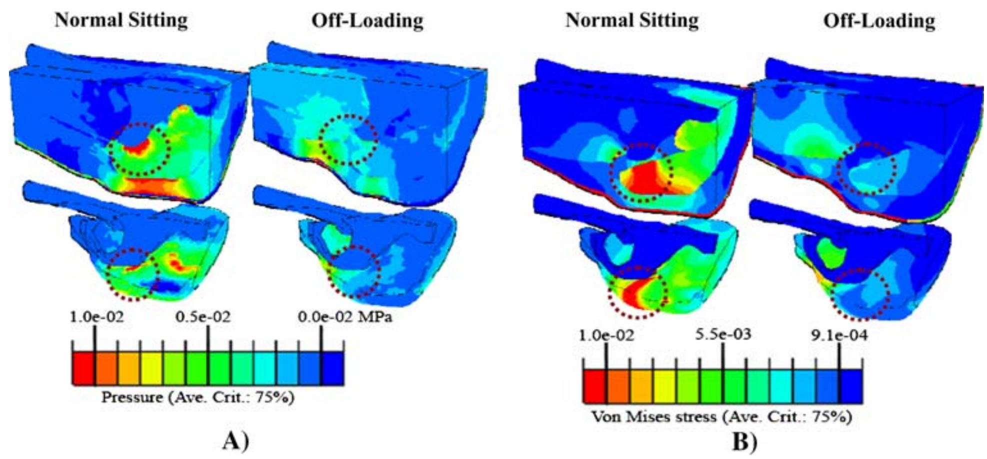

Fig. 4 **a** Internal compressive stress and **b** von Mises stress distributions for the entire structure (*top*) and a group of muscles (*Minimus*, *Medius and Maximus Gluteus)* below ischial tuberosity of the buttock-thigh (*bottom*) predicted for both the *Normal* and *Off-Loading* postures

elements in a simple 2D FE buttock model, found that the maximal compressive stress and displacement generated close to the bony prominences depended on the surface conditions, with the rough compliant surface generating the least compressive stress and tissue deformation. Oomens et al. (2003) [19], using a simple 2D FE model, also studied the mechanical responses of the deep tissues related to cushion properties. They found that using a soft foam layer on the cushion provided a reduction in the normal stresses at the interface and in the deep tissue as the result of an increase in contact areas. These studies suggested an optimal method to reduce interface pressure and stress/strain on the skin and in the deep tissue of the buttock.

Using a rat model, Linder-Ganz and Gefen [13] reported the compressive strain between 3 and 9% within the muscles beneath the ischial tuberosity, which was supported by our data of 6.9% (for the Normal sitting posture) within the muscle in the same area. However, in a later human subject study of Linder-Ganz et al. [14], a substantially higher compressive strain (70–84%) was reported for the gluteus muscle, which deviated from our findings and their previous data on rats. It is thought that this difference may be due to the discrepancies between the material characteristics used in the models and the structural and geometrical features of the joints, bones and soft-tissues simulated. Obviously, more research is needed to elucidate these inconsistencies.

From what has been reported, there are two apparent advances in the current study. First, the current study used a 3D FE buttock-thigh model, which was developed based on the anatomic geometry in a simulated sitting posture. Second, the FE analysis results were from the simulation using the input from the actual interface pressure maps recorded in corresponding sitting posture. Therefore, we believe that results obtained from our current 3D FE analysis provide more realistic prediction for evaluating cushion and seating system design. The current study only applied the established 3D FE buttock-thigh model in two sitting postures, i.e. the *Normal* and *Off-Loading* postures. However, by using interface pressure maps recorded from other sitting postures, this model should be able to provide reasonable estimation of the internal mechanical responses in various sitting postures.

In the predicted soft tissue compressive strain, there are some locations with negative values, which indicate an increase in tissue thickness (Fig. 3). This phenomenon may be the consequence of the incompressibility of the soft tissue. In this model, we used a first order polynomial elastic *Moony-Rivlin* model [7] with *Poisson ratio* $\cong$ 0.485 [15] to represent the nearly incompressive characteristic of biological tissue. Therefore, when some locations, such as the area beneath the ischial tuberosity, endure large compressive deformation, the soft tissue may be pushed to the neighboring locations, which results in a slight local increase of the tissue thickness.

The von Mises stress, rather than the shear stress, was analyzed in this study. Although it still is uncertain what mechanical parameters are the most relevant to tissue damage [19], evidence supports that living cells are more vulnerable to deformation than to a high hydrostatic pressure [4]. Therefore, the von Mises stress, which is related to the deformational energy stored in the material [13, 19, 23], was analyzed in this study to identify the risk of possible tissue damage by sitting load [19, 23].

There are limitations of current study. The first is that the viscoelasticity of the soft tissue was not considered. The viscoelasticity nature of biological soft tissues has been documented and quantified in the literature for ligaments [25], tendon [10], cartilage [22], and heart and skeletal muscle [3, 21]. As the loading time elapses, the viscoelasticity of the soft tissue may generate stress relaxation in the deep tissue of the buttock. Therefore, a model which does not include the viscoelasticity of the material may result an overestimation of the mechanical stress distribution within the examined material. However, the omission of the viscoelasticity of the material may not have great effect on results of the current study because the study was to compare the mechanical responses obtained from the *Normal* and *Off-Loading* postures in otherwise the same mechanical and physiological conditions. In their latest study, Palevski et al. [20] reported the viscoelastic behavior of the gluteus muscle in the transverse direction. Further improvement in our FE model should incorporate the quantitative formulation of the stress relaxation and shear moduli provided in their study.

Another limitation is the assumption of isotropic and passive characteristic for the muscle. Although this assumption might create some inaccuracy in current FE prediction, it is considered acceptable for the current study. This is because that, in a sitting posture, the activity of muscles in the buttock-thigh area is generally negligible while the muscle is presumably a padding material, which endures compressive load. In this sense, the muscle fibers, which may generate an anisotropic characteristic of the material in tensile contraction, do not express much anisotropy in compression. In addition, the recognition of the muscle tone in our FE simulation [15] may also compensate part of this limitation.

From the current study, it can be concluded that the pressure relief provided by the *Off-Loading* posture was not only on the superficial tissues, but created profound effect in reducing the mechanical stress within deep buttock tissues. Therefore, incorporating the *Off-Loading* posture into seating device design for wheelchair users may prove beneficial in preventing sitting related PU in this population.

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