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Computational studies of the biomechanical efficacy of a minimum tissue deformation mattress in protecting from sacral pressure ulcers in a supine position

Maayan Lustig | **Amit Gefen**

Department of Biomedical Engineering, Faculty of Engineering, Tel Aviv University, Tel Aviv, Israel

Correspondence
Amit Gefen, Ph.D., Professor of Biomedical Engineering, The Herbert J. Berman Chair in Vascular Bioengineering, Department of Biomedical Engineering, Faculty of Engineering, Tel Aviv University, Tel Aviv, 69978, Israel.
Email: gefen@tauex.tau.ac.il

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Abstract

Sustained soft tissue exposure to localised deformations is a trigger for the formation of pressure ulcers. Immersion and envelopment are critical benchmarks that determine comfort and the pressure ulcer risk mitigation, as they have considerable influence on tissue stress concentrations near bony prominences. In the present study, we developed a computer modelling framework for quantifying the extent by which optimal envelopment disperses tissue stress concentrations near the sacrum. To compare the risk of developing a sacral pressure ulcer while lying supine on a regular foam mattress with respect to lying on a specialised, minimum tissue deformation mattress (which closely conforms to the body contours), we used a three-dimensional anatomically-realistic model of the adult female buttocks. The strains and stresses in the sub-dermal soft tissues reached peak values of 65% and 2.4 kPa for the regular mattress, respectively, but always remained below 45% and 1.2 kPa for the minimum tissue deformation mattress, which indicates longer safe times for supine support on the latter mattress. Our work demonstrates that alleviation of localised, sustained stress concentrations through good immersion and envelopment of the support surface protects from pressure ulcers, and has the potential to relieve chronic pain which is associated with the pressure ulcer risk.

KEYWORDS
biomechanical phenomena, computer simulation, immersion, preventive health care, soft tissue injury

Key Messages

- envelopment is a key benchmark for comfort and pressure ulcer risk mitigation
- using computer modelling we quantified the value of optimal envelopment
- we analysed the alleviation of sacral soft tissue stress concentrations

Abbreviations: 3D, Three-dimensional; COF, Coefficient of friction; FE, Finite element; MRI, Magnetic resonance imaging; MTDM, Minimum tissue deformation mattress; PU, Pressure ulcer; RFM, Regular foam mattress; VOI, Volume of interest.

- a minimum tissue deformation mattress is effective in dispersing tissue loads
- the observed tissue load relief is also beneficial in reducing chronic pain

1 | INTRODUCTION

Soft tissue exposure to sustained deformations and stress concentrations, which typically occur at the vicinity of the sacrum, calcanei, scapula, and occiput in supine lying, is the triggering event and driving force for the formation of pressure ulcers (PUs), according to the International Guideline for PU Prevention and Treatment.[1] Immersion and envelopment are two critical benchmarks that determine the comfort and PU risk mitigation levels provided by medical support surfaces,[2-4] as they have a remarkable effect on the stress concentrations near bony prominences.[5] Immersion is the depth into which a patient's body penetrates when the patient is placed on a certain support surface, whereas envelopment is the ability of that support surface to conform around the same patient's body. Without immersion, envelopment is not feasible, as the support surface remains flat (such as in the case of a rigid spine board), but immersion can occur without much envelopment. High immersion with little envelopment, which is characterised by an actual body-mattress contact area that is substantially less than the potential surface area of the body that may be placed in contact with the support surface (i.e., the entire surface area of the back of the body, for a supine patient), is ineffective for dispersing localised soft tissue loads and thereby, for protecting from PUs. However, where the degrees of immersion and envelopment increase together, the body-mattress contact area increases as well, which distributes the patient's bodyweight over an area that approaches the maximum coverage of the entire body surface, thereby leading to a drop in the localised tissue stress concentrations near the bony prominences.

The relations between the levels of the soft tissue stress concentrations near bony prominences and the degree of envelopment during weight-bearing postures are highly complex. These relations depend on the anatomical and geometrical features of the individual patient, the material composition and structure of the support surface and any overlies, the specific body position (including the elevation of the head of the bed), scarring or other soft tissue lesions with abnormal stiffness

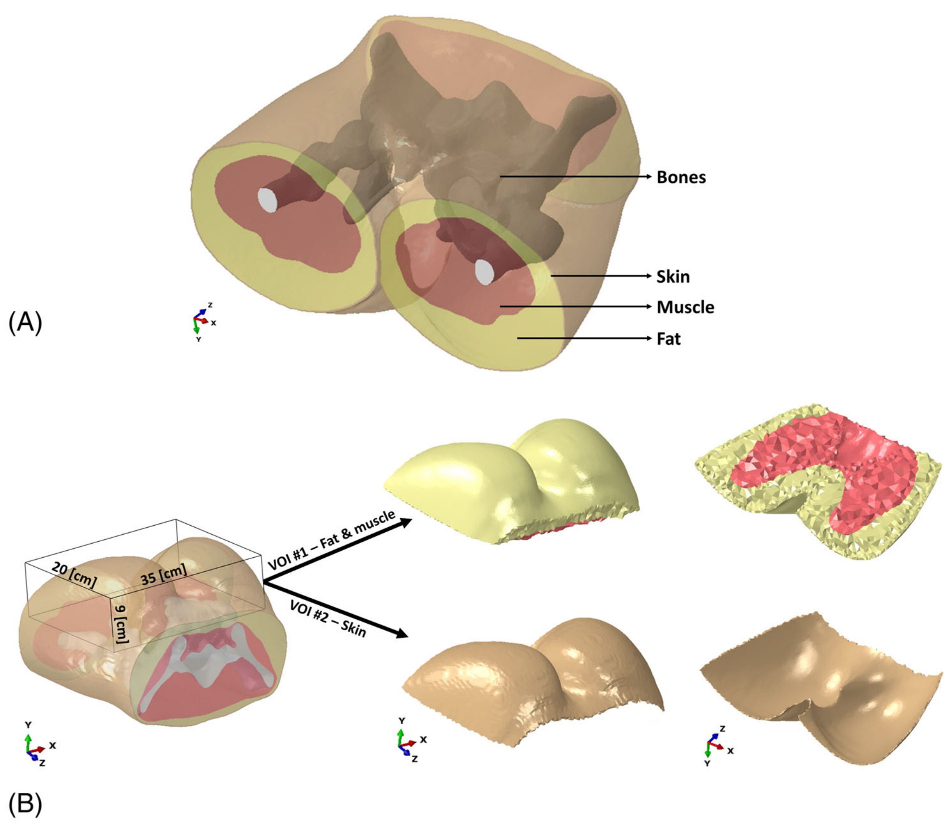

FIGURE 1 Geometry of the computational (finite element) model: (A) The undeformed buttocks incorporating the skin, fat and skeletal muscle tissue structures that envelop the pelvic and sacral bones and the proximal femurs. (B) The volumes of interest (VOIs) of the soft tissues at the sacral region, for computational analyses of skin (VOI#1) and subdermal (fat and muscle; VOI#2) tissue exposures to strains and stresses

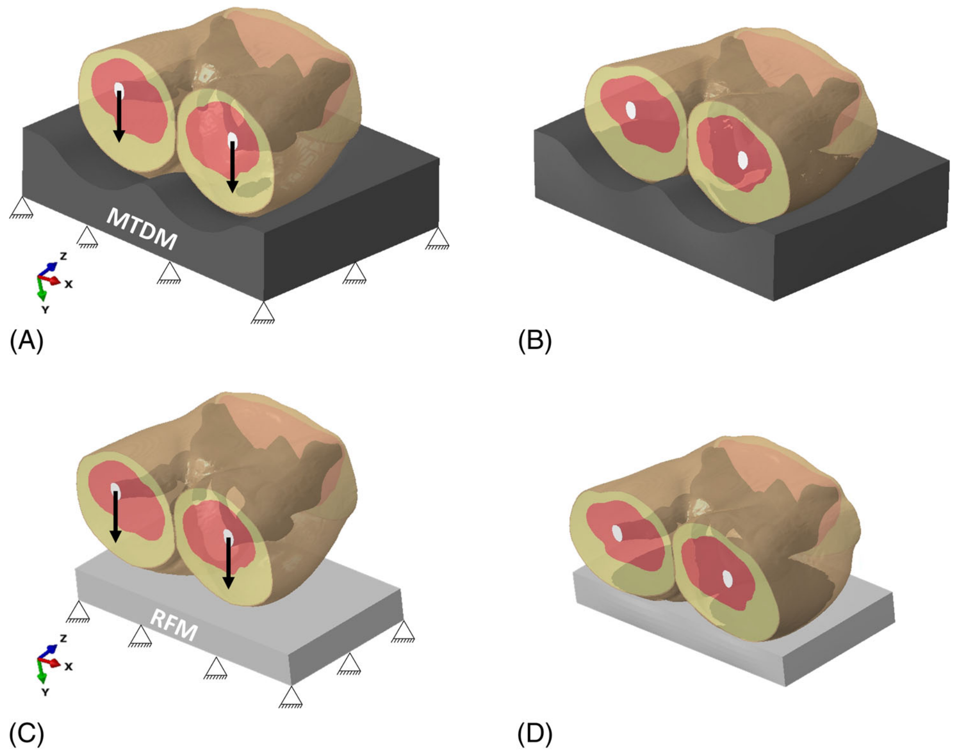

FIGURE 2 Boundary and loading conditions for the two buttocks model variants: The partial bodyweight that represents the mass of the pelvic region is applied on the skeleton (black arrows) while the inferior aspect of the support surface is fixed for all (translational and rotational) motions. This process repeats for the minimum tissue deformation mattress (MTDM) and the regular foam mattress (RFM) which is used as a comparator. The tissue configurations are shown for the (A) undeformed (off-loaded) and (B) deformed buttocks on the MTDM and likewise, for the same (C) undeformed and (D) deformed buttocks on the RFM. The undeformed buttock configurations represent the instant in time before weight-bearing, where the body had just touched the support surface, but the body-mattress contact is still minimal

and the muscle tension, to mention a few examples of such potentially influential factors. Computer modelling and simulations, for example, by means of the finite element (FE) method, are powerful in revealing and quantifying the effects of good envelopment on dispersing soft tissue stress concentrations.[5] Accordingly, computational methods are highly useful for establishing contemporary evidence that good envelopment is protective from PUs, based on the current aetiological knowledge which directly connects between internal sustained soft tissue stress concentration levels and the PU risk.[1]

It is therefore surprising that so little computer modelling work had been published to date, concerning the positive influence that envelopment has on alleviating soft tissue loads, for patients who stay in bed, and, therefore, depend on the envelopment quality of their support surface for safety and well-being. Specifically, Lee and colleagues[6] addressed this issue by developing a FE model of the body on foam support surfaces, but only used their modelling to predict the resulting contact pressures (which are directly measurable and do not require modelling), and importantly, they did not analyse the internal tissue loading levels which are the most relevant information to the aetiology of PUs. The work of Luo et al[7] provided a somewhat more detailed description of the internal tissue loading state, but examined the scapular region which is a substantially less typical anatomical location for a PU in a supine position with respect to the sacrum; their work was also limited to a flat foam support surface that can provide only limited envelopment because of the elastic nature of such flat foams.

Accordingly, there is an important gap in the literature where currently, it is unknown to which extent can optimal envelopment alleviate the internal soft tissue loads near the sacrum, for better comfort and PU risk reduction. The aim of this study was therefore, to develop a FE modelling framework for quantifying the extent by which optimal envelopment can disperse the soft tissue stress concentrations at the sacral region which are associated with supine lying.

2 | METHODS

2.1 | Geometry

To compare the biomechanical risk of developing a sacral PU while lying supine on a minimum tissue deformation mattress (MTDM; Carital Optima, manufactured by MediMattress Oy, Helsinki, Finland) with respect to lying on a regular foam mattress (RFM), a three-dimensional (3D) anatomically-realistic model of the buttocks, previously developed and experimentally validated by our research group, has been used here.[8,9]

In brief, the above computational model is based on magnetic resonance imaging (MRI) slices of the buttocks of a 28-year-old healthy woman, which were segmented into bony structures (sacral bones and proximal femurs), skeletal muscle, fat, and skin tissues. The maximum model dimensions were 23 cm × 38.2 cm × 22.3 cm (length × width × height). The segmented MRI slices were 3D reconstructed using the ScanIP module of the Synopsys Simpleware software package (Synopsis Inc, Mountain View, CA) (Figure 1A). Two volumes of interest (VOIs) within the soft tissues at the sacral region of the buttocks were defined for further calculations of tissue exposures to mechanical strains and stresses during the supine weight-bearing on each mattress type: Subdermal (fat and skeletal muscle) tissues in VOI#1, and skin in VOI#2 (Figure 1B).

The MTDM was modelled phenomenologically (i.e., without considering the details of the specific mechanisms in the product), as a mattress structure that closely conforms to the anatomy of the buttocks, through high envelopment performance which is achieved by means of a proprietary (non-alternating) reactive minimum air pressure support surface technology (Figure 2A,B).[10] The comparator RFM was modelled as a flat, 5-cm-thick, standard (homogenous) medical foam mattress (Figure 2C,D).

2.2 | Constitutive behaviour and mechanical properties of the model components

In Table 1 we provide a glossary of the key engineering terms used here to describe the material models for the current computational analyses, for the convenience of readers with non-engineering backgrounds. The constitutive laws and mechanical properties of all the model components were considered to represent a homogenous-isotropic material behaviour, and specific parameter values were adopted from the literature (Table 2). Specifically, the pelvic and sacral bones were assumed to be a linear-elastic, isotropic material with elastic modulus of 7 GPa and a Poisson's ratio of 0.3.[11-13] The skin, subcutaneous fat and skeletal muscle tissues were assumed to behave hyper-elastically, as Neo-Hookean materials[9,14,15] with the following strain energy density function W:

$$W = C_{10}\left(\overline{I_1} - 3\right) + \frac{1}{D_1}\left(J_{el} - 1\right)^2 \quad (1)$$

where:

- C_{10} is a material parameter representing the shear modulus (μ_0) and defined as $C_{10} = \frac{\mu_0}{2}$
- $\overline{I_1}$ is the first invariant of the right Cauchy-Green deformation tensor defined as $\overline{I_1} = \overline{\lambda_1}^2 + \overline{\lambda_2}^2 + \overline{\lambda_3}^2$ whereas $\lambda_i \ (i = 1,2,3)$ are the principal stretch ratios
- D_1 is a material parameter representing the bulk modulus (K_0) and defined as $D_1 = \frac{2}{K_0}$
- J_{el} is the determinant of the deformation gradient tensor

TABLE 1 Glossary of key engineering terms used here to describe the material models for the current computational analyses

Term	Definition
Bulk modulus (K_0)	A parameter describing the ability of a material to resist potential changes in volume when subjected to compression from all aspects
Deformation gradient tensor (F)	A measure of the extent of deformation in a material, which maps material elements in a pre-deformed (reference) configuration into corresponding elements in the deformed configuration of the same material
Elastic modulus (E)	A parameter describing the ability of a material to resist potential changes in length when subjected to uniaxial tension or compression
Hyperelasticity	The non-linear behaviour of an elastic material that does not dissipate internal energy through release of heat when subjected to large deformations
Neo-Hookean material	A specific type of hyperelastic behaviour that is commonly used in biomechanical research to describe a nonlinear stress–strain behaviour of an elastic material subjected to large deformations
Poisson's ratio (υ)	The ratio of the lateral strain (forming perpendicularly to an applied stress) in a deformed material, over the longitudinal strain (which is parallel to the direction of the applied stress) in the same material
Right Cauchy-Green deformation tensor (C)	The square of the local change in distances within a material because of deformation (defined as $C = F^T F$)
Shear modulus (μ_0)	A parameter describing the ability of a material to resist transverse deformations

TABLE 2 Mechanical properties of the model components and characteristics of the finite element mesh

Material	Shear modulus μ_0 [kPa]	Bulk modulus K_0 [kPa]	Elastic modulus E [kPa]	Poisson's ratio (υ)	# Of mesh elements
Skin	8	666.67	—	0.494	237 638
Fat	0.8	66.67	—	0.494	314 740
Muscle	0.45	37.5	—	0.494	125 215
Bone	—	—	$7 * 10^6$	0.3	43 240
MTDM	—	—	10	0.3	62 476
RFM	—	—	10	0.3	32 436

Abbreviations: MTDM, minimum tissue deformation mattress; RFM, regular foam mattress.

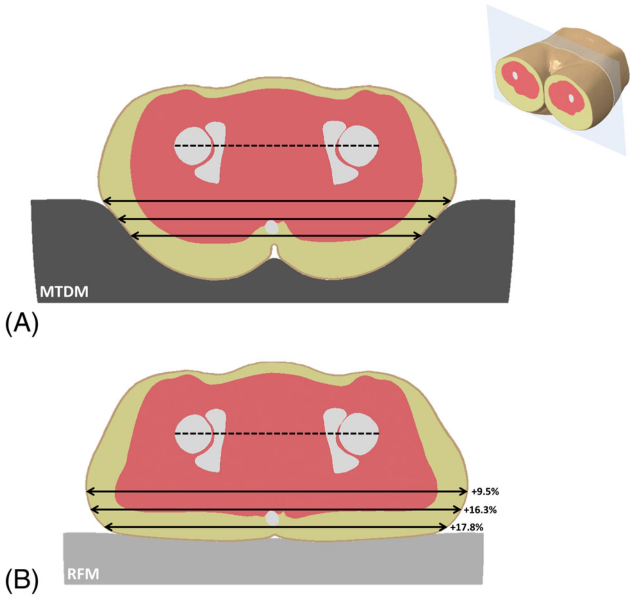

FIGURE 3 Transverse cross-sections of the buttocks during supine lying on the (A) minimum tissue deformation mattress (MTDM) and (B) regular foam mattress (RFM). It is shown that despite that the same buttocks is modelled in the two panels, the contours of the body are substantially different between these two mattresses and that the shape distortions of the undeformed buttocks are minimal on the MTDM and considerable on the RFM. The black arrows are measures of the flattening of the soft tissues and in particular, the sideway tissue spreading on the RFM, with respect to that occurring on the MTDM at corresponding anatomical locations, as follows: (a) 2 cm above the tip of the sacrum; (b) at the superior tip of the sacrum and (c) at the inferior level of the sacrum. The excessive sideway spreading of the buttocks on the RFM with respect to the MTDM case is indicated for these three anatomical locations and is shown to increase towards the direction of the support surface. The dashed lines (between the femoral heads) show that the scales of the MTDM and RFM images are identical

Both the MTDM and RFM were assigned the same stiffness properties of a soft support surface, that is, an elastic modulus of 10 kPa and a Poisson's ratio of 0.3 (Table 2), likewise based on published literature and consistent with our previously reported work.[9,10,16,17] This was aimed to isolate the specific effect of the high envelopment feature of the MTDM on the loading state of the sacral soft tissues, by avoiding potential interferences with the influence of the support surface stiffness level.

2.3 | Boundary conditions

Downward displacements of up to 6.4 cm were applied on the femurs to simulate a force of 90 N acting perpendicular to the mattresses, which represented the partial bodyweight, that is, the mass of the pelvic region that is subjected to gravity during supine lying (Figure 2).[8,9] Furthermore, the inferior surfaces of both mattress types were fixed for translations and rotations in all directions. The femurs were only allowed to move along the vertical (*y*-axis) direction, towards the mattress, to simulate the body immersion as a result of gravity. The (sliced) body surfaces at both ends of the MRI scan (i.e., towards the torso at the proximal end and towards the legs at the distal end) were fixed for displacements along the body axis (*z*-axis). Tied interfaces were defined between all the tissue boundaries. Frictional sliding was defined between the buttocks and the mattress (for each mattress type), with the coefficient of friction (COF) set to 0.4.[8,9,17,18] Selection of the same COF value for the two mattress types was again decided upon in order to isolate the effect of the envelopment, per se, on the tissue loading state. Lastly, frictionless self-contact was set over the skin surfaces on each side of the inner thighs.

2.4 | Numerical method

All the components of the two model variants (MTDM and RFM) were meshed using four-node linear tetrahedral elements, by means of the ScanIP module of Simpleware (Synopsis Inc.) (Table 2). The FE simulations were set up

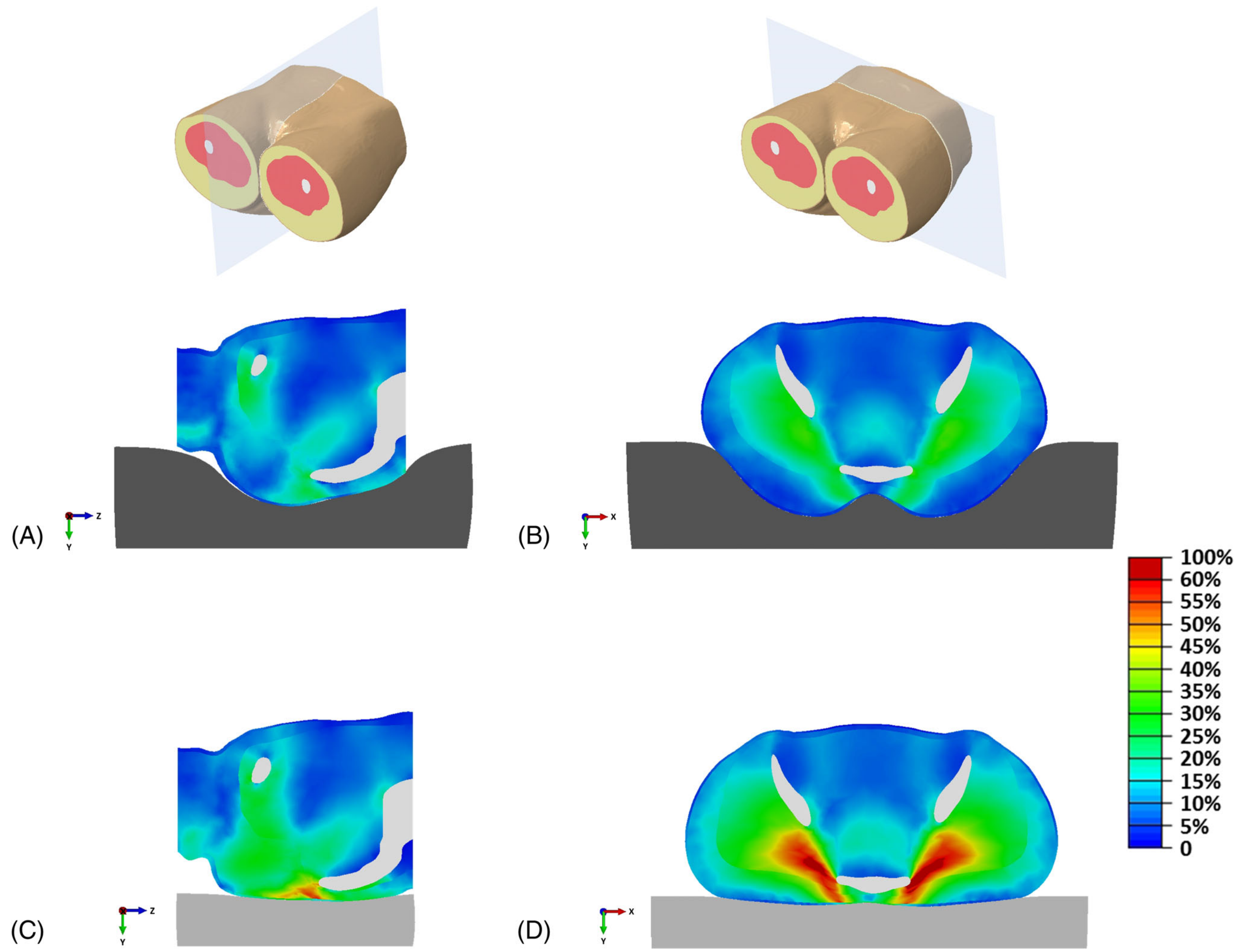

FIGURE 4 Strain distributions in the soft tissues of the buttocks, shown in: (A) sagittal and (B) transverse cross-sections for supine lying on the minimum tissue deformation mattress (MTDM) and similarly, in (C) sagittal and (D) transverse cross-sections of the (same) buttocks on the regular foam mattress (RFM). The sites of concentrated tissue strains are below the right and left aspects of the sacrum and are considerably greater for the RFM condition

using the Abaqus/CAE 2020 software suit (Dassault Systèmes, Vélizy-Villacoublay, France).[19] The runtime of each model variant ranged between 10–15 hours using a 64-bit Windows 10-based workstation with an Intel Xeon CPU E5-2620 2.00 GHz and 64 GB of RAM.

2.5 | Model validation and outcome measures

To validate the current modelling framework, we determined the sideway soft tissue spreading on the MTDM with respect to that occurring on the RFM at three corresponding transverse cross-section levels, as follows: (a) 2 cm above the tip of the sacrum; (b) at the superior tip of the sacrum and (c) at the inferior level of the sacrum (Figure 3). The percentage increase of sideway tissue spreading on the RFM with respect to the corresponding MTDM values at the above 3 planes (Figure 3) were compared with the experimental data reported by Soppi and colleagues who used low-radiation dose computed tomography imaging to study the body contour changes on the MTDM (see Figure 2 in[10]). Specifically, we measured an increase of 9.5%, 16.3% and 17.8% in sideway soft tissue spreading on the RFM with respect to the MTDM values, from the superior to the inferior transverse body planes, respectively (Figure 3). These values are well within the ranges of sideway tissue spreading as reported by Soppi et al,[10] which provides validation to the present modelling framework. Accordingly, we continued to analyse the distributions of soft tissue strains and stresses in the buttocks, for each mattress condition, and within the two VOIs, representing deep (fat and muscle; VOI#1) and superficial (skin;

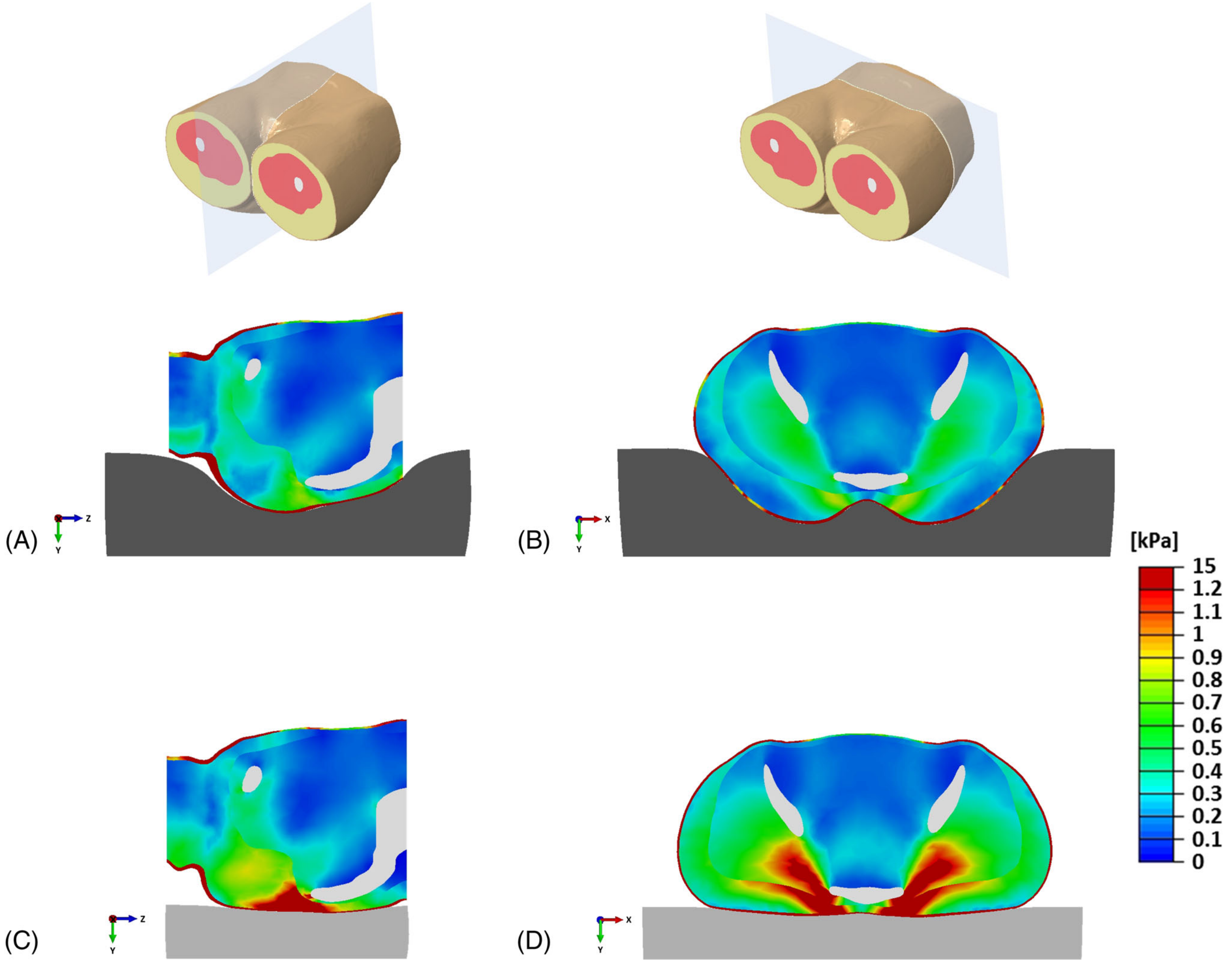

FIGURE 5 Stress distributions in the soft tissues of the buttocks, shown in: (A) sagittal and (B) transverse cross-sections for supine lying on the minimum tissue deformation mattress (MTDM) and similarly, in (C) sagittal and (D) transverse cross-sections of the (same) buttocks on the regular foam mattress (RFM). The sites of the soft tissue stress concentrations are below the right and left aspects of the sacrum and are considerably greater for the RFM condition

VOI#2) tissues (Figure 1), in order to plot the respective stress exposure histogram charts as further reported in the Results section. Any *Z*-score greater than 3 or less than −3 for the point strain and point stress (individual element) data were outlier values, and, thereby, were excluded from the above VOI analyses.

3 | RESULTS

The strain (Figure 4) and stress (Figure 5) distributions in the soft tissues of the buttocks, shown in sagittal and transverse cross-sections for supine lying on the MTDM and RFM, demonstrated that the sites of concentrated tissue strains and stresses are below the right and left aspects of the sacrum and are considerably greater for the RFM condition. Further quantitative analyses of the volumetric soft tissue exposures to strains and stresses above the median levels (Figure 6) indicated that for the subdermal tissues (VOI#1), the area under the curve (AUC) for the RFM is 2-times (Figure 6A) and 3.3-times (Figure 6B) larger than for the MTDM, respectively. Similarly, for skin (VOI#2), the AUC for the RFM is 10-times (Figure 6C) and 6-times (Figure 6D) larger than for the MTDM, respectively. The strains in VOI#1 (subdermal tissues) reached a peak value of 65% for the RFM, but always remained below 45% for the MTDM, and, likewise, the maximal VOI#1 stress on the RFM was 2.4 kPa, however, stresses were always below 1.2 kPa for the MTDM (Figure 6). Consistent with the above, the skin strains in VOI#2 exhibited a peak of 36% for the RFM, but for the MTDM, the skin strains were always below 20%; the VOI#2 tissue stresses on the RFM maximised at 15 kPa but were not more than 10 kPa for the MTDM

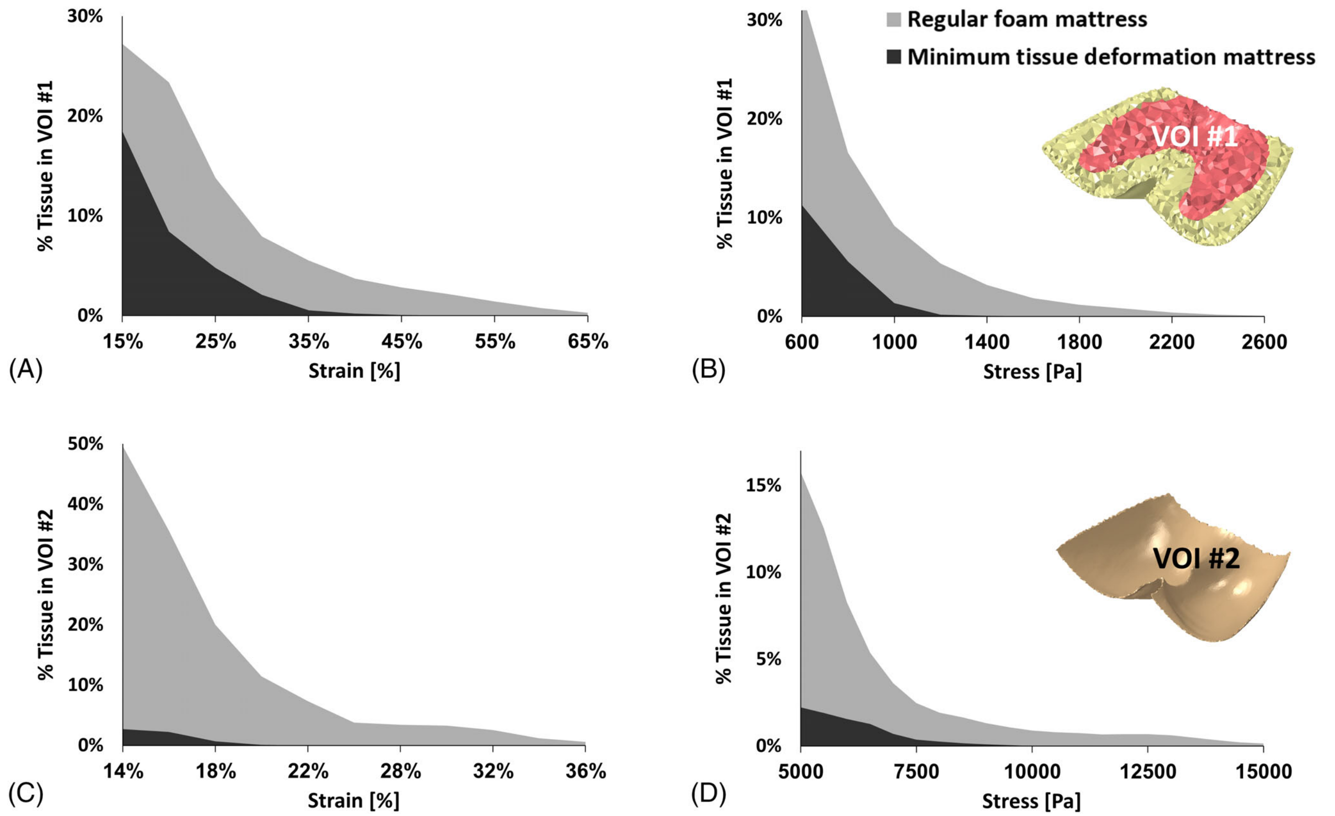

FIGURE 6 The volumetric soft tissue exposures to (A) strains and (B) stresses above the median levels for fat and muscle tissues (VOI#1) exhibit similar trends to the corresponding skin exposures to (C) strains and (D) stresses (VOI#2). Across all these studied outcome measures, the exposures of soft tissues to strains and stresses are consistently and remarkably greater for the regular foam mattress (RFM) than for the minimum tissue deformation mattress (MTDM)

(Figure 6). Therefore, across all the aforementioned outcome measures, the exposures of sacral soft tissues to strains and stresses were consistently and remarkably greater for the RFM than for the MTDM (Figure 6).

4 | DISCUSSION

The shape that a support surface takes as it interacts with the body of an individual patient is a critical factor in the overall risk of that patient to develop a PU, and, when some sensation is present, on the level of discomfort or pain that the patient would experience.[20] Adequate envelopment is an essential physical requirement for lowering the intensities of interface pressures and shear on the skin of patients who stay in bed, simply because when the level of the envelopment increases, more of the body surface area is in contact with the support surface and, thereby, the bodyweight loads are transferred more uniformly.[3-5] The larger the contact area for the bodyweight load transfer is, the lesser the localised cell and tissue distortions and tissue stress concentrations are.[1] Accordingly, a support surface that continuously provides good envelopment, which is delivered consistently across patients, regardless of the patient body characteristics and the body position, fulfils the primary requirement for being effective in PU prevention.[2]

With that said, focusing on interface pressures is deceiving, as stress concentrations in subdermal soft tissues near bony prominences such as the sacrum may be an order-of-magnitude greater, because of the geometrical irregularities (i.e., the relative sharpness of the bony surfaces and the steep tissue stiffness gradients between bones and overlying soft tissues.[21] It is therefore surprising that so little is known about the contribution of a good envelopment to lowering the level of deep tissue stress concentrations in patients who are at-risk. Whilst our published work provided important insights on this phenomenon for wheelchair cushion users, primarily by means of computational modelling methods,[5,16,22-24] mattresses received less attention in the literature in general, and in our reported work in particular. Excluding a study on the contribution of minimising patient migration in bed to lowering the shear stress concentrations in deep soft tissues at the sacral region,[25] the power of advanced computational modelling was not fully utilised to determine the potential influence of envelopment on lowering deep tissue stress concentrations. Our purpose in this study was to address this important question, by focusing on an MTDM technology versus standard foam support as a reference support surface case, to quantitatively demonstrate the importance of envelopment in lowering the biomechanical PU risk through alleviation of internal, localised deep tissue loading.[1] Indeed, our current analyses demonstrated that the exposures of soft tissues to strains and stresses were consistently and remarkably greater for the RFM than for the MTDM (Figure 6), which is a first robust biomechanical research evidence that high envelopment protects supine patients from sacral DTIs.

Other than reducing the risk for sacral DTIs, dispersing any localised deep tissue deformations and stress concentrations offers better comfort and relief of pain for those who are fully or partially sensate. There are direct links between the level of risk for bed-acquired PUs and the intensity of the discomfort or pain sensation experienced by such (fully or partially) sensate patients, which stem from the fundamental aetiology of PUs.[1,26] Namely, these are the (a) inflammatory, (b) nociceptive and (c) ischaemic pathways of pain, which are parallel to the routes of progression of the tissue damage caused in the formation of a PU.[1,26]

An important contributor to discomfort and pain is the mechanical irritation applied by the increasing interstitial pressures on nociceptors, as an inflammatory oedema builds up, which causes direct "nociceptive pain".[1,26,27] This nociceptive pain may be further amplified by the direct mechanical loading on primary nerve endings when the skin breaks-down, as in a Category-2 or deeper open PUs.[1,26,27] Clearly, any sustained shear loading that is associated with the bodyweight forces may further contribute to obstructing the vasculature and, thereby, aggravating the biochemical tissue conditions.[1] The result is a multifactorial, complex pain, to which the above inflammatory, nociceptive and ischemic pain components are contributing cumulatively, and with the share of each depending on the specific patient and support surface conditions. Importantly, there is the strong coupling of this complex pain mechanism with the main vicious cycle of PU development, in which direct deformation-inflicted, inflammatory, and ischaemic cell and tissue damages also interact together.[1,26,27]

As explained above, discomfort and pain should play a critical role in protecting the body from PUs in the general patient population, provided that the muscle power and cognitive capacity to respond to these sensations are present. When the latter are impaired, but a patient is still able to sense the discomfort or pain, the exposure to sustained, localised tissue deformations and stress concentrations (Figures 4 and 5) may cause unbearable suffering to the patient and serious difficulties to the care providers, who are often family members. It is well established that reducing the general pain typically improves the overall mental and physical conditions of at-risk patients, allowing them to better respond (physically) or communicate (verbally) about any changes or sensations that may indicate a forming PU.[27] In other words, as the general pain intensity is relieved, patients typically become more sensitive and responsive to the localised discomfort or pain sensations that may indicate an early-stage PU-related tissue damage. Moreover, relieving the general pain allows patients to sleep better, so that they (and their care providers) have less fatigue, more stamina and therefore, better physical and mental endurance in coping with their condition. Moreover, patients with overall reduced pain are also likely to need lower doses of pain and sleep medications (which improves their cognitive state), as well as less strenuous care regimens. Reducing the general discomfort and pain in patients who stay in bed is therefore a pivotal clinical goal in the treatment of patients who are considered at-risk of PUs, as the author and his group had demonstrated in a series of patient case studies investigated in this regard.[27] The present analyses add the vitally important, quantitative perspective to the aforementioned, previously published patient case series analysis.[27] Altogether, the work demonstrates that alleviation of localised, sustained tissue deformations and stress concentrations through good immersion and envelopment of the support surface, as in the case of the MTDM, protects from PUs, and also, has the potential to relieve chronic or general pain which is directly associated with the above PU risk.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Amit Gefen https://orcid.org/0000-0002-0223-7218

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