

ORIGINAL ARTICLE

The biomechanical efficacy of a dressing with a soft cellulose fluff core in protecting prone surgical patients from chest injuries on the operating table

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Abstract

Pressure ulcers are soft-tissue damage associated with tissue exposure to sustained deformations and stress concentrations. In patients who are prone for ventilation or surgery, such damage may occur in the superficial chest tissues that are compressed between the rib cage and the support surface. Prophylactic dressings have been previously proven as generally effective for pressure ulcer prevention. In this study, our goal was to develop a novel computational modelling framework to investigate the biomechanical efficacy of a dressing with a soft cellulose fluff core in protecting prone surgical patients from chest pressure ulcers occurring on the operating table, due to body fixation by the Relton-Hall frame. We compared the levels of mechanical compressive stresses developing in the soft chest tissues, above the sternum and ribs, due to the trunk weight, whilst the body is supported by the Relton-Hall frame pads, with versus without the prophylactically applied bilateral dressings. The protective efficacy index for the extremely high stresses, above the 95th-percentile, were 40.5%, 25.6% and 24.2% for skin, adipose and muscle, respectively, indicating that the dressings dispersed elevated soft-tissue stresses. The current results provide additional support for using soft cellulose fluff core dressings for pressure ulcer prophylaxis, including during surgery.

KEYWORDS

computer model, deep tissue injury, pressure ulcer/injury prophylaxis, protective efficacy, surgical positioning

Key Messages

- chest pressure ulcers are common in prone patients undergoing spinal surgery
- the chest tissues are compressed between the rib cage and the fixation frame

Abbreviations: COF, Coefficient of friction; EF, Finite element; IOA, Intraoperatively-acquired; OR, Operating room; OT, Operating table; PUs, Pressure ulcers; PEI, Protective efficacy index; RHF, Relton-Hall frame; SEH, Stress exposure histogram; 3D, Three-dimensional; VOI, Volume of interest; ZPSB, Zetuvit Plus Silicone Border.

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- computer modelling was used to determine chest tissue stresses during surgery
- stress concentrations occurred in the sternal soft tissues and above the ribs
- dressings with soft cellulose fluff core disperse these stress concentrations

1 | INTRODUCTION

Pressure ulcers (PUs), also known as pressure injuries, are soft-tissue damage associated with tissue exposure to sustained deformations and stress concentrations, typically in the vicinity of bony prominences or under a stiff, skin-contacting medical device.¹ In patients who are prone for ventilation or surgery, such damage may occur in the superficial chest soft tissues that are compressed between the rib cage and the support surface. In spine surgeries, where the proning may last at least 3 and up to 10 hours (often excluding the time required for the preoperative preparations), chest injuries are particularly common, comprising 19% of the total lesions, similarly to the anatomical share of facial injuries due to proning.²⁻⁴ However, damage to the soft tissues of the chest is also known to occur in other clinical scenarios involving prolonged proning and immobilisation, such as invasive ventilation of patients with acute respiratory failure caused by coronavirus disease 2019 (COVID-19).^{5,6} As the incidence of intraoperatively-acquired (IOA) PUs in surgical prone patients is approximately 44% (in a study including N = 307 patients), of which 19% occur on the chest, the incidence of IOA chest PUs is ~8%. In other words, these wounds should be expected in nearly 1 of 10 prone surgical patients, with those patients undergoing longer surgeries and having greater bodyweights being at the highest risk.²

Preventing IOA PUs in the operating room (OR) is much more challenging than in other settings, due to the special conditions that apply in the OR setting. In particular, it is not feasible to reposition a patient during surgery, and the support surface needs to be relatively firm and thin to facilitate stability of the patient on the operating table (OT), which is required for surgical precision.^{7,8} In addition to these general considerations that apply in any surgical scenario, spine surgeries involve an even greater biomechanical risk to tissue health and integrity, due to the nature of the body support in these specific surgeries. The trunk of the prone patients is often supported by the Relton-Hall frame (RHF) device (Figure 1A), which consists of four pads (typically covered by foam or gel) that can be tilted medially to fix and stabilise the patient in the prone surgical position. The RHF is designed to avoid excessive pressures on the abdomen and thereby, reduce the haemorrhage during the

surgical procedure.⁹ However, this implies that the RHF concentrates the bodyweight forces to the small and limited contact regions with the pads, so that the weight of the upper trunk is supported almost exclusively by the two chest pads, above which, the thin chest soft tissues are sandwiched and compressed by the rigid and curved rib structures. Not surprisingly, IOA bi-lateral chest PUs, as shown in Figure 1B,* are commonly reported in association with the use of RHF.¹⁰ Accordingly, new approaches for lowering the risk for the occurrence of IOA chest PUs in prone surgical patients positioned by

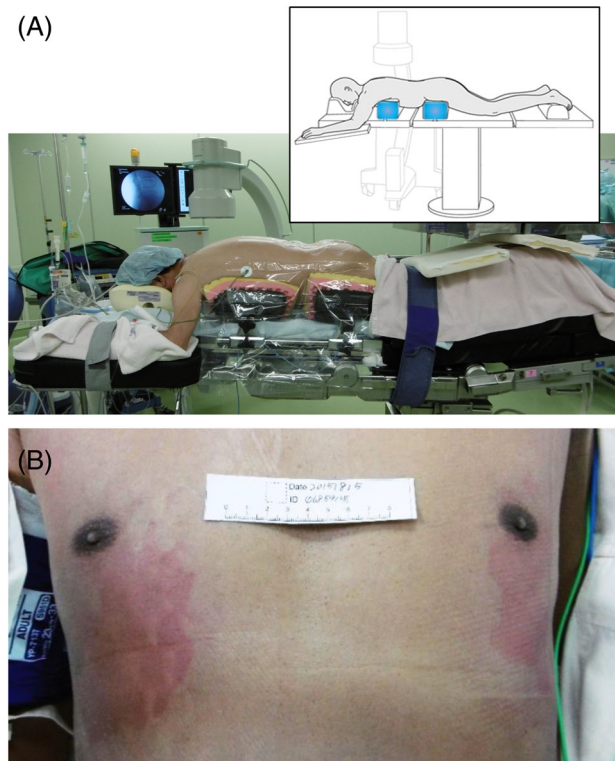


FIGURE 1 Prone positioning in the operating room: (A) A patient lying prone on the operating table whilst being supported by a foam-padded Relton-Hall frame (RHF) designed to avoid excessive pressures on the abdomen and reduce haemorrhage during the surgical procedure. (B) Intraoperatively-acquired, bilateral chest pressure ulcers associated with prone positioning on an RHF. The pattern of the erythema on the left side of the body clearly conforms the locations of the ribs. The images are courtesy of Professor Norihiko Ohura, M.D., Dept. of Plastic, Reconstructive and Aesthetic Surgery at Kyorin University School of Medicine, Tokyo, Japan

means of RHF's should be developed, to specifically address and mitigate the localised compressive forces and the resulting stress concentrations in the soft tissues covering the rib cage.

Prophylactic dressings have been proven as effective for PU prevention, both when the risk is due to bodyweight forces or caused by skin-contacting medical devices¹¹⁻¹⁹; yet, the vast majority of the published literature, as well as the 2019 International Guideline for Pressure Ulcer/Injury Prevention and Treatment,²⁰ focussed on the usage of *foam*-based dressings for these tasks. Hence, there is paucity of information concerning the biomechanical protective efficacy of dressings made of

alternative advanced materials, and only recently, such information begins to appear in the literature, which serves the important goal of expanding the scope of candidate dressing designs for prophylaxis beyond the foam-based dressing structures.²¹⁻²⁵

In this study, our goal was to develop a novel computational modelling framework to investigate the biomechanical efficacy of a dressing with a soft cellulose fluff core, in protecting prone surgical patients from IOA chest PUs occurring on the OT, due to body fixation by means of an RHF. Specifically, we compared the levels of mechanical compressive stresses developing in the soft tissues of the chest, above the sternum and ribs, due to

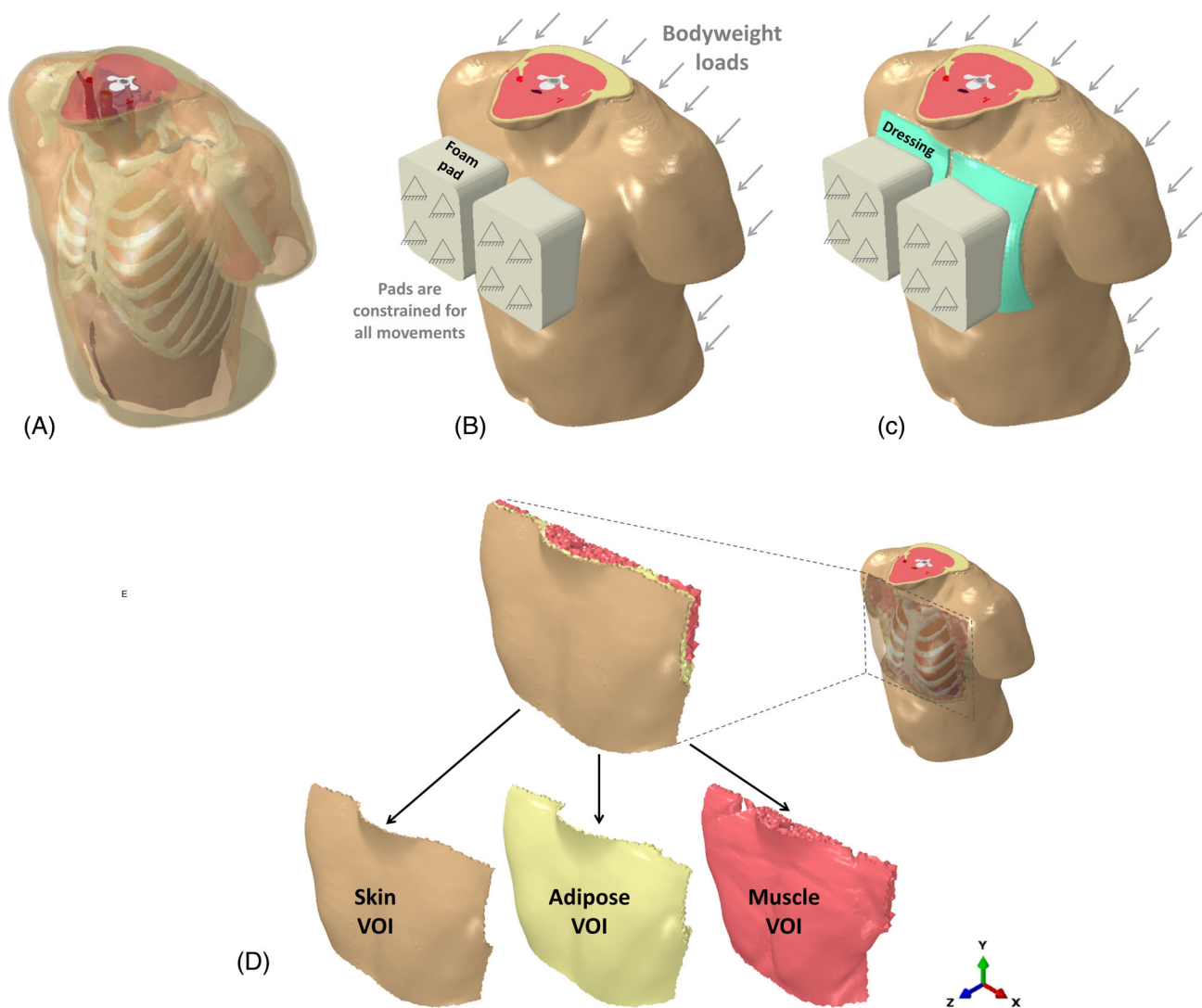


FIGURE 2 Geometry and boundary conditions of the computational (finite element) modelling framework: (A) The torso model, which includes skin, adipose and skeletal muscle tissue layers over the rib cage. (B) The torso and two foam pads of the Relton-Hall frame (RHF), which support the chest, without and (C) with the prophylactically applied bilateral dressings. The weight of the torso was simulated in both cases, and the inferior surfaces of the RHF pads were constrained for all movements to mimic the locking of the RHF in position. (D) The volumes of interest (VOIs) in the soft-tissue layers above the ribcage, for the further analyses of skin, adipose and muscle tissue exposures to the compressive tissue stresses associated with the bodyweight forces

the trunk weight, whilst the body is supported by the RHF pads, with versus without the prophylactically applied bilateral dressings.

2 | METHODS

2.1 | Geometry

To evaluate the biomechanical efficacy of a dressing with a soft cellulose fluff core in protecting prone surgical patients from chest injuries on the OT, due to fixation by means of an RHF, a three-dimensional (3D), anatomically realistic model of the torso was developed and applied.

The geometry of the upper body model was based on 267 transversal images of the torso, imported from the Visible Human Project anatomical database.²⁶ The distance between sequential transversal images was 2 mm, and the maximum model dimensions were 53.4 cm × 55 cm × 31.5 cm (length × width × height). Each image was segmented to create partitioning into multiple tissue segments. The dataset was then reconstructed to a 3D geometry containing 3D representation of the segmented tissues, which included skin, adipose and skeletal muscle layers over the rib cage (Figure 2A). We used the ScanIP module of the Synopsys Simpleware software package (Synopsis Inc, Mountain View, CA, USA) for the segmentation and meshing of the different tissues. The geometry of the pair of foam pads of the RHF, which provides bilateral support to the thoracic cage in the prone surgical position, was created and meshed in the Abaqus/CAE 2020 finite element (FE) software suit (Dassault Systèmes, Vélizy-Villacoublay, France).²⁷ The dimensions of these RHF pads were 16.5 cm × 13.3 cm × 10 cm (Figure 2B,C).

The dressing product studied here as a prophylactic measure to protect the chest of prone surgical patients was the Zetuvit[®] Plus Silicone Border (ZPSB) dressing, also known as RespoSorb Silicone Border (manufactured by Paul Hartmann AG, Heidenheim, Germany). This dressing contains soft cellulose fluff blended with a fluid-retaining superabsorber that are enclosed in a non-woven envelop. This complex dressing structure was represented phenomenologically in the current modelling, by homogenising it to a soft elastic and isotropic layer with effective mechanical behaviour under compression (detailed further) as measured and reported in our previously published work.²³ The geometry of the pair of prophylactic dressings applied to the chest was created and meshed in Abaqus/CAE 2020. The dressing dimensions were 20 cm × 15 cm × 0.5 cm (Figure 2B,C).

Three volumes of interest (VOIs) of the soft-tissue layers of the chest covered by the dressings, namely, the skin, adipose and muscle tissues, were defined for

further calculations of tissue exposures to the compressive stresses occurring in the prone position on the RHF, with or without the prophylactic dressings (Figure 2D). These VOIs were defined as the corresponding tissue layers directly under the dressing projections and in-between the bilateral dressings (Figure 2D).

2.2 | Constitutive behaviours and mechanical properties of the model components

The constitutive laws and mechanical properties of all the model components were considered to represent homogenous-isotropic material behaviours, and specific parameter values were adopted from the literature (Table 1). In particular, the clavicles, ribs, sternum and costal cartilages were assumed to be linear-elastic, isotropic materials,²⁸⁻³³ whereas the skin, adipose and muscle tissues were considered to behave hyperelastically, as Neo-Hookean materials,³⁴⁻³⁶ according to the following strain energy density function W :

$$W = C_{10}(\bar{I}_1 - 3) + \frac{1}{D_1}(J_{el} - 1)^2 \quad (1)$$

where:

- C_{10} is a material parameter representing the shear modulus (μ_0) and defined as $C_{10} = \frac{\mu_0}{2}$
- \bar{I}_1 is the first invariant of the right Cauchy-Green deformation tensor defined as $\bar{I}_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2$, whereas λ_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

The RHF pads and dressings were assumed to be isotropic and linear elastic. The RHF pads were assigned stiffness properties in the midrange of standard medical foams, that is, a compressive elastic modulus of 75 kPa and a Poisson's ratio of 0.3.³⁷⁻⁴² The compressive elastic modulus and Poisson's ratio of the ZPSB dressings were set as 10 kPa and 0.3, respectively, based on published laboratory test results characterising the compressive stiffness of these particular ZPSB dressings²³ (Table 1).

2.3 | Boundary conditions

Incremental downward displacements reaching 2.1 cm were applied along the spine to result in a

TABLE 1 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]	Density ρ [kg/m ³]	Poisson's ratio ν	Number & type of elements
Skin	3.4	40	—	1085	0.45	299 740 Tetrahedral elements
Adipose	0.8	66.67	—	850	0.494	557 547 Tetrahedral elements
Muscle	0.45	37.5	—	1000	0.494	1 250 452 Tetrahedral elements
Ribs and sternum	—	—	$10 \cdot 10^6$	1800	0.3	93 115 Tetrahedral elements
Costal cartilage	—	—	$5 \cdot 10^5$	1200	0.3	25 161 Tetrahedral elements
Clavicle	—	—	$7 \cdot 10^6$	1000	0.3	5014 Tetrahedral elements
Foam pads	—	—	75	1000	0.3	13 164 Tetrahedral elements
Dressings	—	—	10	1000	0.3	956 Linear brick elements

target bodyweight force (ie, a reaction force with the RHF pads) of 135 N acting perpendicular to the RHF pads, which represented the mass of the torso subjected to gravity during proning (Figure 2B,C). Under these displacements, the spine was only allowed to move along the z-axis, that is, towards the RHF pads, to simulate the body immersion due to gravity. The sliced body surfaces at both ends of the torso geometry data set (ie, towards the head at the proximal end, and towards the legs at the distal end) were fixed for displacements along the body axis (y-axis), to represent the resistance to tissue deformations formed by the proximal and distal body parts at the sliced torso surfaces. The inferior surfaces of the RHF pads were constrained for all movements, to mimic the locking of the RHF in position in preparation for surgery.

Tied interfaces were defined between all the tissue boundaries. For the model variant which included the ZPSB prophylactic dressings, 'tied contact' conditions were set at the skin-dressing contacts, to simulate the adhesive attachment of the dressings. Between the outer layer of the dressings and the RHF pads, frictional sliding was defined, with the coefficient of friction (COF) set to 0.4.^{37,43-47} For the model variant without the dressings, frictional sliding was defined between the skin and the RHF pads, and the skin-pad COF was also set to 0.4.^{37,43-47}

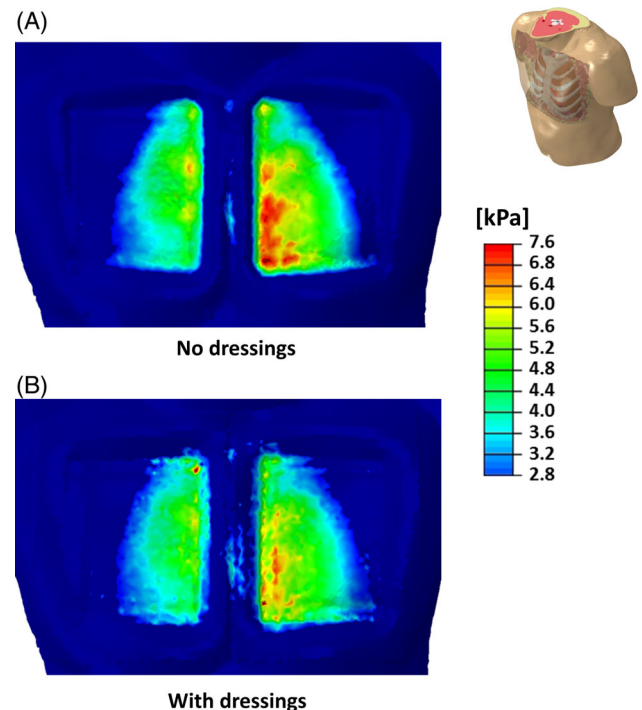


FIGURE 3 The distribution of compressive stresses above the third quartile (75th-percentile) of the stress domain in skin without (A) and with (B) the prophylactically applied bilateral dressings, whilst the chest is being pressed against the pads of the Relton-Hall frame due to the weight of the torso. Note the reduction of the elevated stresses above the left aspect of the distal sternum (xiphoid process) in (A) by the left dressing (B)

2.4 | Numerical method

The tissue components of the model variants were meshed using four-node linear hybrid tetrahedral elements (C3D4H), by means of the ScanIP module of Simpleware. The RHF pads and ZPSB prophylactic dressings were meshed in the Abaqus/CAE 2020 software, using 10-node quadratic tetrahedral elements (C3D10) and 8-node linear brick elements (C3D8R), respectively (Table 1). All the FE simulations were set up using the Abaqus/CAE 2020 software. The runtime was approximately 44 hours for each simulation, 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 | Outcome measures

We analysed the distributions of compressive stresses in the soft tissues of the chest for both model variants (i.e., with or without the dressings), and within each of the three VOIs (contralateral skin, adipose and muscle) (Figure 2d), in order to plot the stress exposure histogram (SEH) charts per each VOI (as further reported in the Results section). Any Z-score greater than 3 or less than -3 for the point stress (individual element) data were considered to be outlier values and, thereby, were excluded from the above VOI-SEH analyses. Lastly, the protective efficacy index (PEI) values of the ZPSB dressing, in its function to protect the chest of a prone surgical patient, were calculated from the above SEHs for the compressive stresses above the 95th-percentile (that is, for the extreme non-outlier tissue stress values in the tissue stress concentrations), and per each VOI/tissue type (Figure 2D), as in our previous published work^{21,23,24}:

$$PEI [\%] = 100 \times \frac{A_{nd} - A_d}{A_{nd}} \quad (2)$$

where A_{nd} and A_d are the areas under the SEH curves of the no-dressing and with-dressing simulations, respectively. Of note, a dressing with poor biomechanical effectiveness would have a corresponding PEI of zero or near-zero (as it will not change the tissue exposure to high stresses, and therefore, A_{nd} and A_d will be approximately equal). Contrarily, the hypothetical, ideal prophylactic dressing would have a PEI = 100%, as it would reduce the tissue exposure to high stresses down to zero, so that $A_d = 0$ (which is a theoretical case that is unlikely to occur in the real-world).

3 | RESULTS

The compressive stress distributions above the third-quartile (75th-percentile) of the stress domains in the

layered soft tissues of the chest (skin, adipose and muscles) during proning, with versus without the prophylactically applied bilateral dressings, are shown in Figures 3-5. The bilateral stress state is asymmetric at the skin surface and throughout the skin and subcutaneous tissue depth, as could be expected given the inherent body asymmetry and the positioning of the pair of RHF pads, which is not symmetric as well, to conform to the body left-right asymmetry. For skin, the dressings clearly alleviated the elevated stresses, especially above the left aspect of the distal sternum, near the xiphoid process (Figure 3). At the deeper soft-tissue layers of the chest, that is, adipose and muscle, the dressings effectively dispersed the tissue stress concentrations above the ribs near the costochondral joints (for rib numbers 1-4), particularly at the left body side (Figures 4-5).

The SEHs for soft-tissue stresses above the third-quartile (75th-percentile) and the related magnifications of tissue stress exposures above the 95th-percentile of the corresponding stress domains are plotted at the left-hand and right-hand side frames in Figure 6, respectively. These results demonstrate that the prophylactic application of

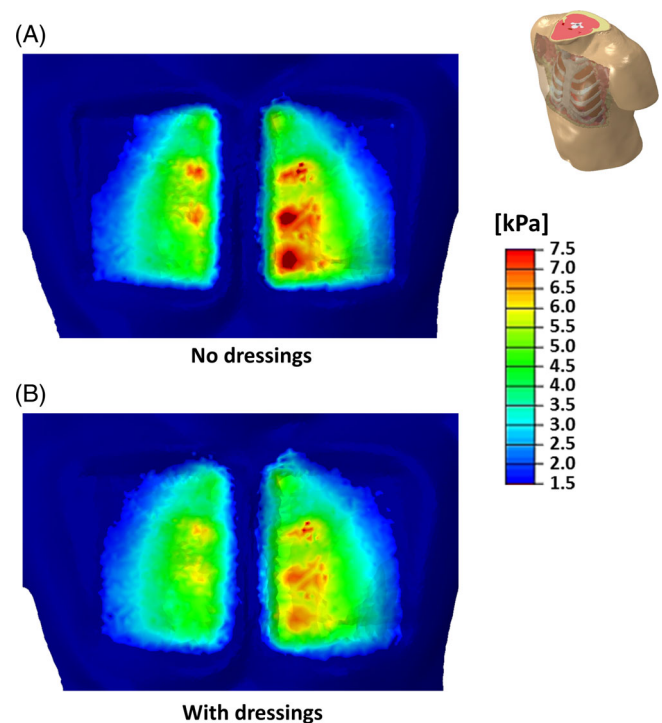


FIGURE 4 The distribution of compressive stresses above the third quartile (75th-percentile) of the stress domain in adipose tissue without (A) and with (B) the prophylactically applied bilateral dressings, whilst the chest is being pressed against the pads of the Relton-Hall frame due to the weight of the torso. Note the compressive stress concentrations above the ribs (near the costochondral joints), particularly at the left body side in (A) and their effective dissipation by the left dressing

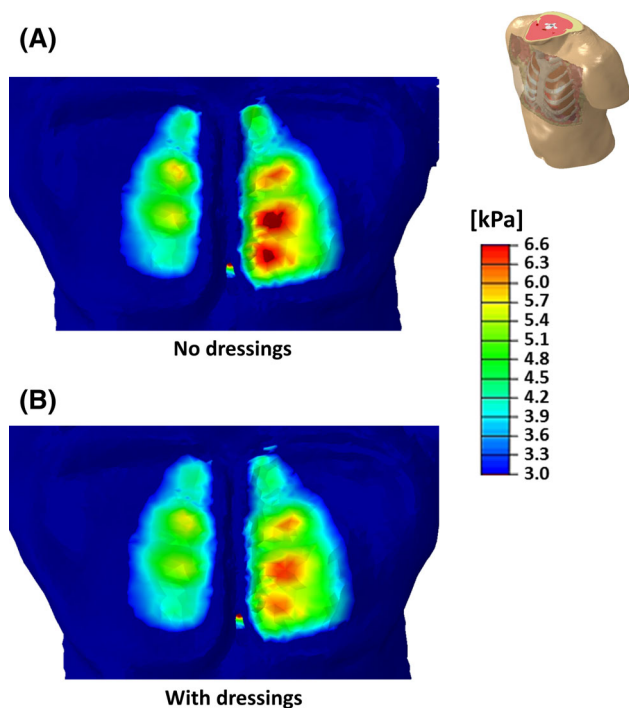


FIGURE 5 The distribution of compressive stresses above the third quartile (75th-percentile) of the stress domain in skeletal muscle tissue without (A) and with (B) the prophylactically applied bilateral dressings, whilst the chest is being pressed against the pads of the Relton-Hall frame due to the weight of the torso. Note the compressive stress concentrations above the ribs (near the costochondral joints), particularly at the left body side in (A) and their effective dissipation by the left dressing

the ZPSB dressings reduced the volumetric exposure to high stresses at both stress ranges and across the entire depth of the layered soft-tissue structure of the chest. The PEI for the extremely high stresses, above the 95th-percentile, were 40.5%, 25.6% and 24.2% for skin, adipose and muscle, respectively, indicating a similar extent of protection provided by the ZPSB dressings across the subdermal tissue depth, and hence, biomechanical effectiveness in prophylaxis considering the typical clinical presentation of a deep tissue injury (Figure 1B).

4 | DISCUSSION

In this study, a novel computational modelling framework was developed and used to investigate the biomechanical efficacy of a dressing with a soft cellulose fluff core, that is, the ZPSB dressing, in protecting prone surgical patients from chest injuries on the OT when patients are fixed in the prone position using an RHF, in preparation for a spinal surgery. Specifically, we compared the levels of mechanical compressive stresses developing in the soft tissues of the chest near the sternum and ribs due

to the bodyweight loads, whilst the body was supported by the RHF pads, with versus without prophylactically applied bilateral ZPSB dressings. The hypothesis was that the use of such dressings helps to alleviate the compressive stresses in the soft tissues of the chest and hence, reduce the risk for IOA chest PUs associated with the surgical proning. Our current findings strongly supported this hypothesis, that is, the ZPSB dressings indeed dispersed the elevated soft tissue stresses, especially in the vicinity of the distal sternum (the xiphoid process) and near the costochondral joints and across the entire tissue depth, that is, in skin, adipose and muscle (Figures 3-6), as required given the typical clinical presentation of the damage as a deep tissue injury (Figure 1).

The vast majority of the published literature concerning the biomechanical and clinical efficacy of dressings applied prophylactically concerns foam-based and hydrocolloid dressings, which were historically used for prophylaxis of both bodyweight-induced and medical device-related PUs.¹¹⁻¹⁹ However, other advanced dressing technologies, particularly hydrogel-based dressings, were recently examined for their prophylactic value,^{21,22} and it is important to continue to expand the scope of dressing materials and technologies for prophylactic use, to be able to identify the optimal material compositions and structures for this purpose. IOA PUs present a specific and unique challenge in this regard, as they are at the interface between bodyweight-induced PUs and device-related PUs because the OT, particularly with specialised frames for proning or other surgical positions, is a type of a medical device which cannot be directly classified as a simple “support surface.” Accordingly, although Gefen et al. demonstrated in their published work that an ZPSB dressing with a soft cellulose fluff core effectively protects the sacral soft tissues of supine patients on an intensive care bed,²³ this cannot be extrapolated to the OR setting and to other body positions, which had motivated the current study.

Indeed, only a small number of studies examined the efficacy of dressings applied prophylactically for reducing the risk for IOA PUs, and these were again primarily focussed on foam-based dressings applied to the sacrum and heels of supine patients, for example, in the context of vascular surgery.^{48,49} The few studies reporting clinical outcomes of protecting non-supine surgical patients, which were conducted in Japan, employed silicone-foams and hydrocolloids. Specifically, Kohta and colleagues applied polyurethane film dressings or ceramide 2-containing hydrocolloid dressing to the breast area and iliac crests in the prone position, sacral area and scapulae in the lithotomy position, and the axillae and iliac crests in the lateral position,⁵⁰ recognising that as repositioning is not feasible, protecting these body areas may improve

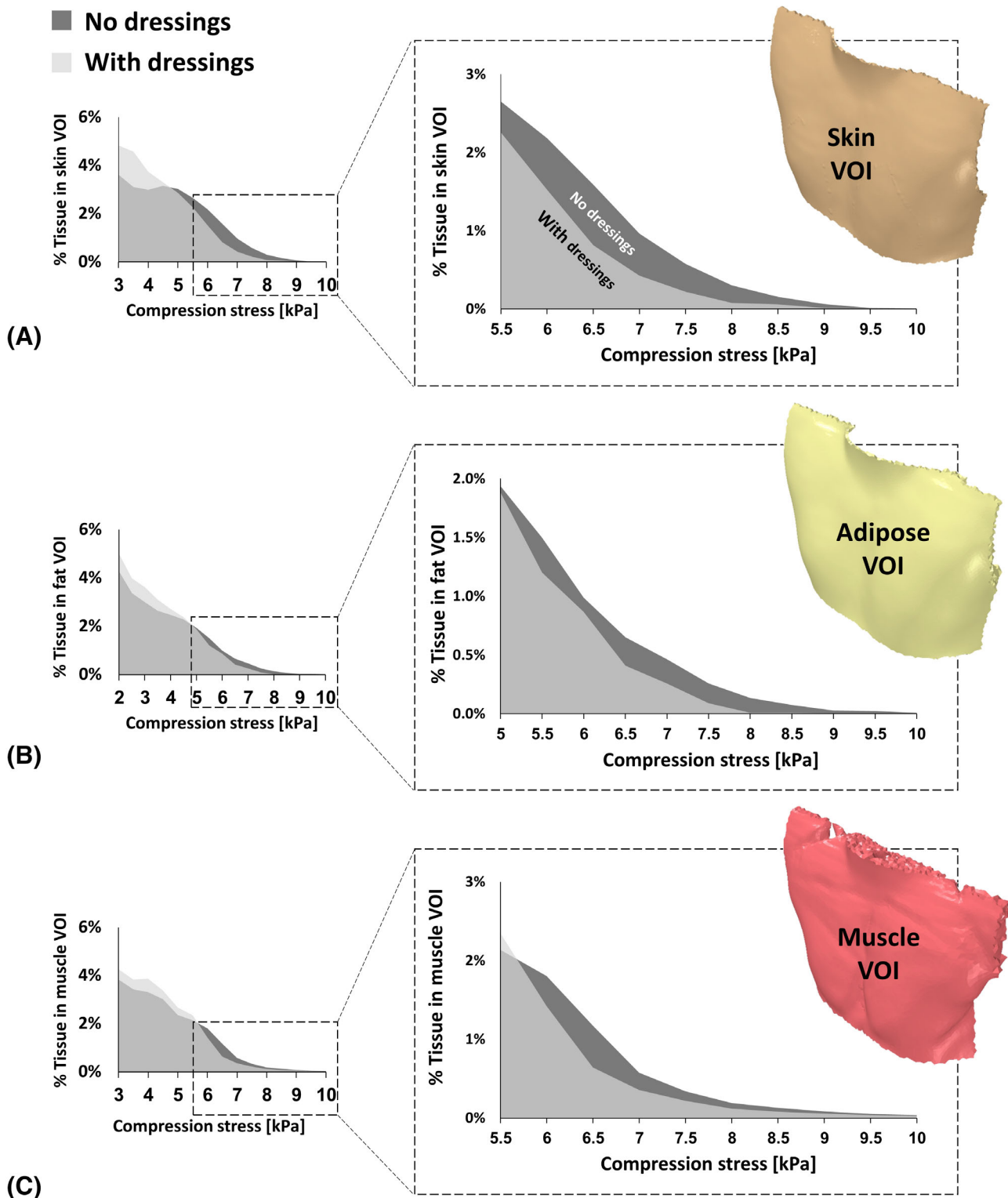


FIGURE 6 Stress exposure histograms, demonstrating the volumetric soft-tissue exposures to above the third quartile (75th percentile) compressive stresses (left panels), and the corresponding magnifications of compressive stress exposures above the 95th-percentile of the stress domain (right frames) in the (A) skin, (B) adipose and (C) skeletal muscle volumes of interest (VOIs). It is shown that the prophylactic application of the dressings reduced the volumetric exposure to both the above-3rd-quartile and the above-95th-percentile stresses across the entire depth of the layered soft tissues of the chest

patient safety.⁵¹ Likewise, Yoshimura et al. reported lower IOA PU incidence rates following application of silicone-foam dressings,⁴ with particularly successful outcomes for overweight prone patients positioned by means of an RHF.³ Our current work is therefore the first to investigate the biomechanical performance of a dressing that is neither foam-based nor made of a hydrocolloid for protecting surgical-prone patients. This provides a new perspective concerning the utility of alternative dressing materials and technologies to protect surgical patients, so that eventually, informed decisions can be made with regards to the selection of prophylactic dressings for this task.

As with any modelling work, assumptions and limitations are inevitable and should be identified and discussed for completeness. First, the anatomy and biomechanical properties of the tissues do not account for a female gender, or for paediatric patients, or for those with rib cage abnormalities. In particular, whilst the modelling considers healthy asymmetry, which is typical and inherent to the Visible Human database,²⁶ it does not consider congenital or acquired chest asymmetries such as pectus excavatum (abnormal development of the rib cage), central obesity or scarring due to (male) mastectomy following breast cancer. Second, we did not consider variations to the surgical-prone position such as the knee chest, kneeling and Jack-knife (Kraske) positions, which may alter the reaction forces on the chest and thereby, affect the PU risk as well as the biomechanical protective efficacy of the ZPSB dressing. Lastly, whilst the ZPSB dressings are expected to lower the stress concentrations in the soft tissues of the chest, they will not necessarily deliver identical protection to different individuals. As with regards to all PUs, the individual level of protection on the same RHF positioning system (and even if all other extrinsic conditions including the applied ZPSB dressings are indistinguishable), would always depend on the patient-specific anatomy and body habitus, their skin fragility, the inflammatory and vascular functions of the skin and subdermal tissues, as well as on the body asymmetry level.^{1,25,52-55}

In conclusion, this study demonstrated the biomechanical efficacy of the ZPSB dressing in protecting surgical, prone patients from IOA chest PUs, which are associated with fixation by means of an RHF. The current modelling specifically revealed that bilateral application of the ZPSB dressings on the chest alleviates compressive stress concentrations in the trunk soft tissues that are induced by the sternum and ribs as reaction forces from the RHF apply. The current results therefore provide additional support for using these dressings with a soft cellulose fluff core for the prophylaxis of bodyweight-induced PUs, including in the OR.

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ENDNOTE

* Note the pattern of erythema on the left side of the body which clearly conforms the locations of the ribs.

DATA AVAILABILITY STATEMENT

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

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