



**HAL**  
open science

## New pressure ulcers dressings to alleviate human soft tissues: A finite element study

Nolwenn Fougeron, Nathanaël Connesson, Grégory Chagnon, Thierry Alonso, Laurent Pasquinet, Manuelle Bahuon, Eugénie Guillin, Antoine Perrier, Yohan Payan

### ► To cite this version:

Nolwenn Fougeron, Nathanaël Connesson, Grégory Chagnon, Thierry Alonso, Laurent Pasquinet, et al.. New pressure ulcers dressings to alleviate human soft tissues: A finite element study. *Journal of Tissue Viability*, 2022, 10.1016/j.jtv.2022.05.007 . hal-03678648

**HAL Id: hal-03678648**

**<https://hal.science/hal-03678648>**

Submitted on 25 May 2022

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# **New pressure ulcers dressings to alleviate human soft tissues: a finite element study**

**Nolwenn Fougeron<sup>1</sup>, Nathanaël Connesson<sup>1</sup>, Grégory Chagnon<sup>1</sup>, Thierry Alonso<sup>1</sup>, Laurent Pasquinet<sup>2</sup>, Manuelle Bahuon<sup>2</sup>, Eugénie Guillin<sup>2</sup>, Antoine Perrier<sup>1,3</sup>, Yohan Payan<sup>1</sup>**

<sup>1</sup> Univ. Grenoble Alpes, CNRS, UMR 5525, VetAgro Sup, Grenoble INP, TIMC, 38000 Grenoble, France

<sup>2</sup> Urgo Research, Innovation & Development, 21300, Chenôve, France

<sup>3</sup> Service de Diabétologie, AP-HP, 75004 Paris, France

Corresponding author:

**Nolwenn Fougeron**

**TIMC Biomeca**

**Univ. Grenoble Alpes, CNRS, UMR 5525**

**Pavillon Taillefer, Allée des Alpes 38700 La Tronche**

E-mail: nolwenn.fougeron@univ-grenoble-alpes.fr

Keywords : Finite Element Analysis, Pressure Ulcers, Dressing, Soft Tissues, Internal Strains

Please cite this article as: Fougeron N, Connesson Nathanaë, Chagnon Gré, Alonso T, Pasquinet L, Bahuon M, Guillin Eugé, Perrier A, Payan Y, New pressure ulcers dressings to alleviate human soft tissues: A finite element study, *Journal of Tissue Viability* (2022), doi: <https://doi.org/10.1016/j.jtv.2022.05.007>.

# Abstract

Pressure Ulcers (PU) are real burdens for patients in healthcare systems, affecting their quality of life. External devices such as prophylactic dressings may be used to prevent the onset of PU. A new type of dressing was designed to alleviate soft tissue under pressure, with the objective to prevent PU and to improve the healing conditions of category-1 and category-2 wounds. The mechanical interactions of this dressing with a generic model of human skin/hypodermal soft tissue was simulated using the Finite Element (FE) method. Different cases with intact skin tissues and injured tissues with a category-2 PU, with and without dressings in place, were modeled. The tissues were deformed under compressive load; internal strains were computed. The results showed a clear benefit from the use of the dressing to reduce the peak internal strains both in the intact and injured tissues models by 17 to 25 %, respectively. The intact soft tissues model was evaluated via sacral pressure measurements performed on one healthy volunteer. Results showed a good agreement between pressure measurements and estimations both with and without the dressing in place; particularly under the bony prominence and in surrounding tissues. As a conclusion, the importance of dressings to maintain a proper biochemical environment for the healing of PU is incontestable. Yet, new concepts of dressings may be developed to prevent the onset of PU, but also to provide local stress and strain reliefs and create mechanical conditions as less damaging as possible for the tissues.

*Word count: 248*

# 1. Introduction

In Europe and North America 7 to 23 % of patients in healthcare facilities develop Pressure Ulcers (PUs) with an increased risk for older patients, people with spinal cord injuries or comorbidities [1]. PUs have terrible consequences on the quality of life of patients including longer hospitalisation time, social isolation and pain.

PUs are localised wounds that propagate in the soft tissues after a detrimental external loading. Short time but intense load application is sufficient to cause tissue wounds while reduced loads applied for an extended period of time can also lead to PUs [2]. Pressure or shear loads applied at the skin level may lead to significant internal strains [3]. When these strains exceed the cell ability to deform, in most cases under bony prominence, this eventually leads to cell death and the development of PUs [4–6].

To reduce the prevalence of PUs, external medical devices are used to redirect external loads away from areas prone to PUs such as the sacrum or the heel. More particularly, dressings have been demonstrated to have a prophylactic effect [7,8]. Finite element (FE) modelling is a known tool to estimate internal tissue strains and stresses, since these quantities cannot be measured *in-vivo* [9]. Consequently, FE models have played a key role to assess the ability of dressings to alleviate soft tissues [10–13]. Most studies report a decrease of the strain energy density and stress in soft tissues, with various dressings [14] considering a supine position. This was also confirmed with head-of-bed elevation [15,16].

However, only few studies focusing on PUs compute the strains correlated to cell death in soft tissues [17] and none of the models proposed in the literature were evaluated with experimental data. Only one study shows the effect of dressings on tissues with a PU [18]. Yet, the used model accounted for a category-4 wound which is not representative of the majority of clinical cases.

Urgo RID is currently developing a new concept of dressing that can be used both to prevent PUs and to improve the healing process for PUs as deep as category-2 PU. To do so, the objective is to reduce the internal strains in the wound and in surrounding tissues. This study aims at developing a parametric FE model of the interaction between intact soft tissues, the Urgo RID dressing and the lying surface. This model was evaluated with regard to pressure estimations which were compared with experimental data. The parametric model was used to assess the prophylactic properties of the dressing and its ability to reduce tissues strains in the presence of a category-2 PU.

## 2. Materials and methods

### 2.1. Dressing model

#### 2.1.1. Dressing description

The new Urgo RID (Urgo Research, Innovation & Development, Chenôve, France) dressing is an improved version of UrgoStart Plus Border® dressing, currently under study and development. The novelty of the dressing consists in adding a deformable and protective layer. This layer is made of alveoli that can be removed in a subject-specific manner in order to unload the wound and its surrounding tissues (Figure 1). To model the mechanical behavior of this new dressing, we proposed to build an FE model with two layers. A first component, referred as “dressing layer 2”, was supposed to model the UrgoStart Plus Border® dressing which is in contact with the skin. In a first approximation this layer was approximated by a single material. The second component, the protective layer was modeled as a deformable layer glued with “dressing layer 2” and was referred as “dressing layer 1”.

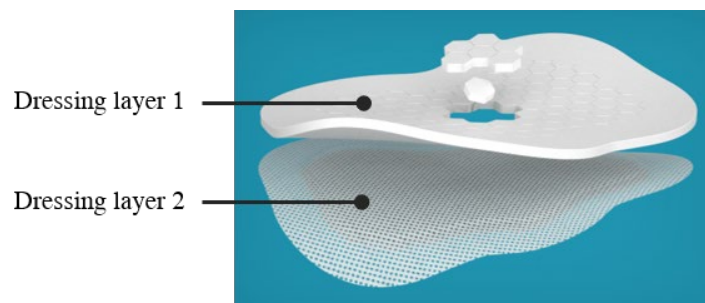


Figure 1: The new dressing design developed by Urgo RID

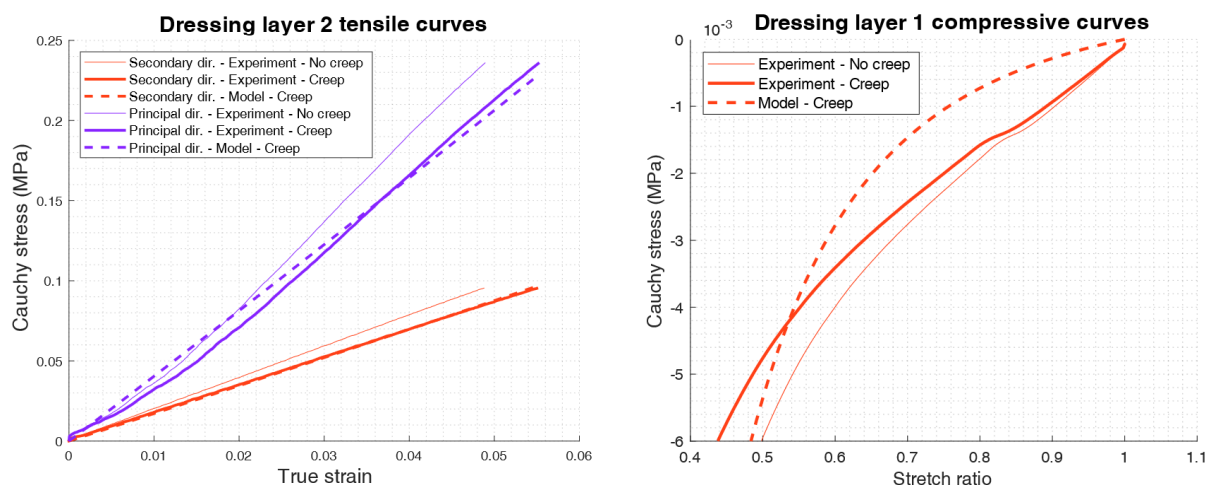
#### 2.1.2. Mechanical tests and modeling of “dressing layer 1”

Compressive mechanical tests were performed on the “dressing layer 1” (Figure 2, right panel). Creep tests showed an increase by 12 % of the stretch ratio for a constant compressive force maintained for 30 min. “Dressing layer 1” was modelled as a compressible homogeneous isotropic material following an hyperelastic Blatz-Ko law [19]. Stretch ratio values were increased by 12 % to account for the creep resulting from the extended used of the dressing. The initial strain shear modulus, 1.00 kPa, was optimized using a curve fitting method with Matlab (Figure 2). “Dressing layer 1” was modelled as a hollow cylindrical layer with a radius of 125.0 mm, a central opening surface of 255.6 mm<sup>2</sup>, larger than the PU surface, and a thickness of 5.2 mm. It was meshed in Ansys Mechanical APDL with 3 612 hexahedral elements (SOLID185).

#### 2.1.3. Mechanical tests and modeling of “dressing layer 2”

25 Tensile mechanical tests were performed on specimens from the “dressing layer 2” cut at 0.0°, 22.5°,  
 26 45.0° and 90.0° according to the orientation of the dressing with the spine (Figure 2, left panel). These tests  
 27 revealed the orthotropy of the dressing. Additional creep tests showed an increase by 16 % of the stretch ratio for  
 28 a constant tension force maintained for 30 min. Thus, the “dressing layer 2” was modeled as a linear homogenous  
 29 orthotropic material. Stretch ratio values were increased by 16 % to account for the creep resulting from the  
 30 extended used of the dressing. Young moduli were optimized using a curve fitting method with Matlab. The  
 31 resulting Young modulus in the principal direction, *i.e.* in the spine direction, was 4.40 MPa, whereas the secondary  
 32 direction, orthogonal to the spine direction in the dressing plane, was 1.80 MPa. An FE inverse method based on  
 33 compression tests performed on both dressing layers was used to assess the Young modulus in the transverse  
 34 direction of the dressing which, eventually, was set to 0.03 MPa.

35 The Poisson coefficient was set to 0.25 according to literature data [15]. This “dressing layer 2” was  
 36 modeled as a cylindrical layer with a radius of 125.0 mm and a thickness of 3.5 mm, and meshed in Ansys  
 37 Mechanical APDL with 2 476 hexahedral elements (SOLID185).



38  
 39 *Figure 2: Material parameters optimization of the dressing layers. The optimization was processed after a correction by*  
 40 *the creep ratio. (Left) “Dressing layer 2”. (Right) “Dressing layer 1” hyperelastic response.*

## 41 2.2. Soft tissues/dressing interaction

### 42 2.2.1. Modeling of the sacral area

43 This study focused on the dressing ability to i) prevent PU within intact soft tissues, and to ii) reduce  
 44 further damage of injured tissues, with a category-2 PU, using parametric FE models. One healthy volunteer (male,  
 45 40 years old, 94 kg, 1.73 m) was included for the modeling and for the experimental setup (described in part 2.3.1).  
 46 The volunteer gave his informed consent as required by the Helsinki declaration (1964). In both intact and injured  
 47 tissues models, two cases of analysis were performed, without and with the dressing placed at the skin surface. In

48 both models the subject was simulated in a supine position on a mattress with linear elastic isotropic homogenous  
 49 properties. The mattress height was set to 50 mm and its Young modulus to 230 kPa [19].

### 50 2.2.2. Intact tissues model

51 The sacral area was modeled as one layer of dermis and one layer of adipose tissues. By means of  
 52 ultrasound images collected onto the volunteer, the dermis thickness was set to 1.3 mm while the adipose tissue  
 53 thickness was 13.3 mm under the bony prominence and 22.3 mm outside the bone. The bone boundary was  
 54 modeled by a portion of sphere with a radius of curvature of 110.0 mm. A bony prominence, approximated by an  
 55 elliptical surface, with a height of 5.2 mm, was added to the model (Figure 4). The length of the sacral area model  
 56 was 250.0 mm, i.e. twice the dressing one, to reduce free boundary effect close to the dressing area. This geometry  
 57 was meshed in Ansys Mechanical APDL using hexahedral linear elements (SOLID185) with a mixed pressure-  
 58 displacement formulation. A mesh convergence study was performed on the displacement of the adipose tissues'  
 59 nodes. Eventually, the complete mesh was composed of 15 936 elements (Figure 5, left panel).

60 The skin was modelled with an Isihara's et al. law [20] (equivalent to a Yeoh constitutive law with the  
 61 parameter  $C_{30}$  equals to zero). Material parameters were optimized using a curve fitting method with Matlab from  
 62 the experimental data of Ni Annaidh et al. [21] who did uniaxial tensile tests on skin samples collected in the sacral  
 63 region (Table 1). The adipose tissue layer was modeled with a Yeoh law [22] and parameters were optimized  
 64 according to the equibiaxial test data of Sommer et al.[23] (Table 1).

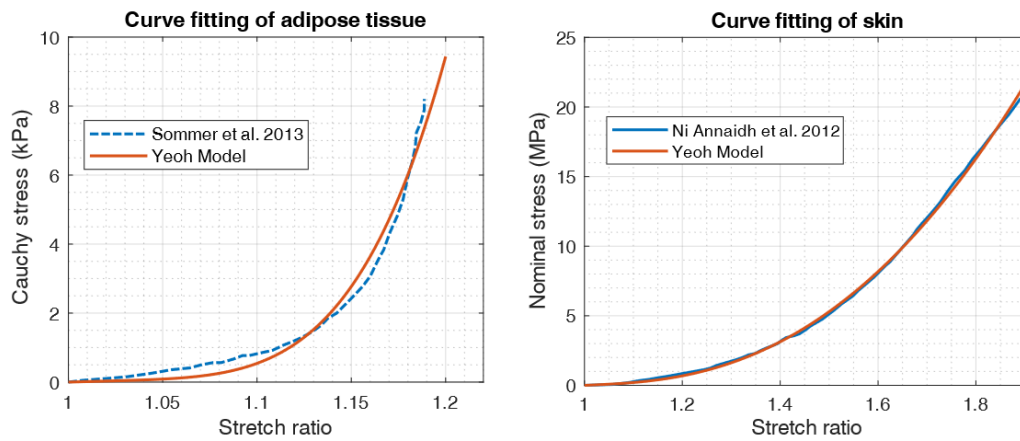
65 All incompressibility parameters were supposed equal and were computed from the formula provided in  
 66 Mott et al. [24]:

$$67 \quad (1) \quad D_1 = D_2 = D_3 = \frac{3(1-2\nu)}{2C_{10}(1+\nu)}$$

68 With  $\nu$ , the Poisson's ratio, set to 0.4999, to account for the nearly incompressibility of soft tissues.

	$C_{10}$ (MPa)	$C_{20}$ (MPa)	$C_{30}$ (MPa)	$D_1$ (MPa <sup>-1</sup> )	$D_2$ (MPa <sup>-1</sup> )	$D_3$ (MPa <sup>-1</sup> )
Adipose tissue	$1.3 \cdot 10^{-4}$	0.0	$12.2 \cdot 10^{-3}$	1.6	1.6	1.6
Skin	$2.7 \cdot 10^{-1}$	1.9	-	$7.5 \cdot 10^{-4}$	$7.5 \cdot 10^{-4}$	-

69 *Table 1: Soft tissues material parameters.*



70

71

Figure 3: Optimization of the material parameters of the adipose tissue (left) and the skin (right)

72

### 2.2.3. Injured tissues model

73

74

75

76

77

A category-2 PU was added in a second parametric model considering that PU are described by circular shapes [25]. A 1.3 mm deep open wound was modeled by removing a cylinder of skin tissue at the center of the model with a radius of 13.0 mm (Figure 4). This geometry was also meshed using hexahedral linear elements (SOLID185) with a mixed pressure-displacement formulation. The resulting mesh was composed of 18 664 elements (Figure 5, right panel).

78

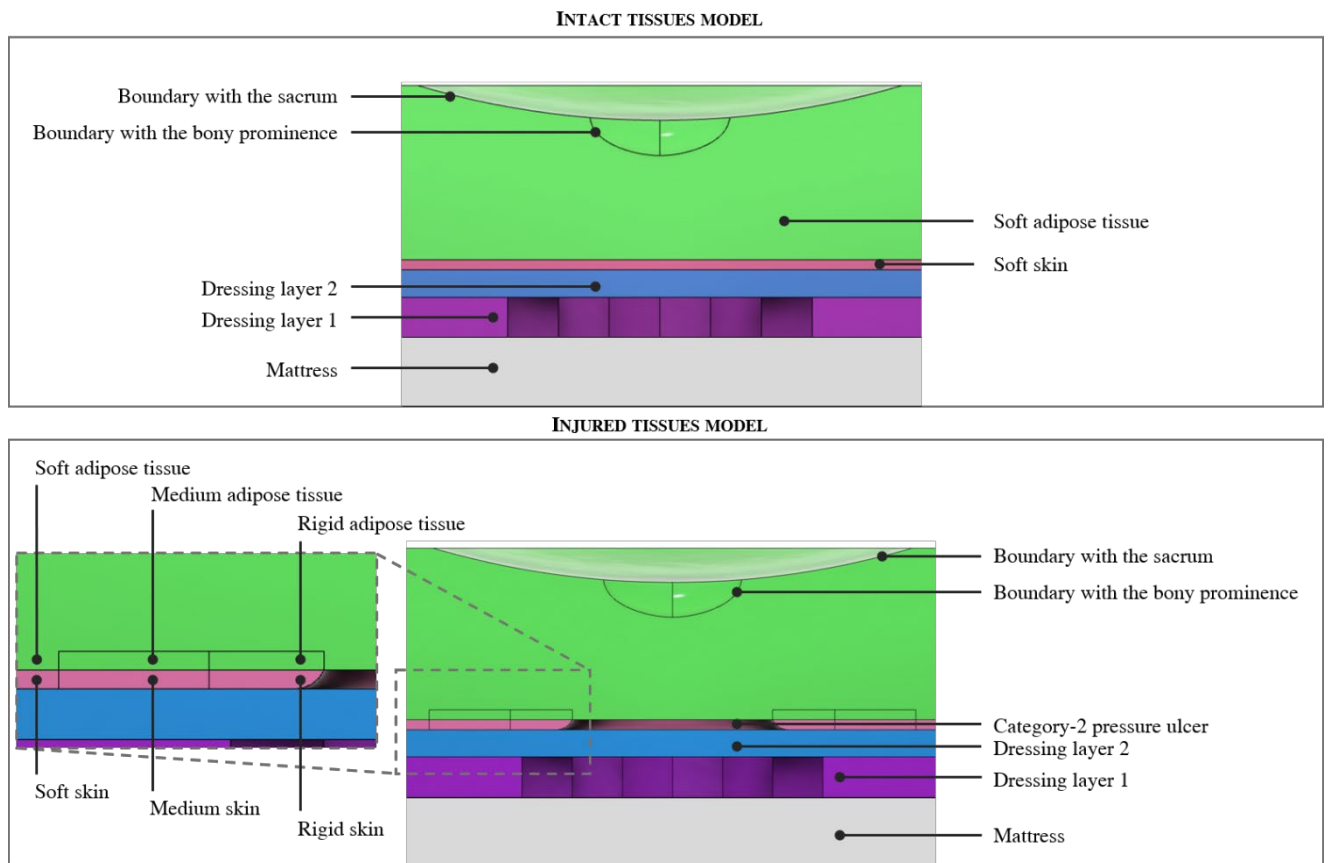
79

80

81

The soft tissues surrounding a PU are usually stiffer than healthy tissues [26]. Three areas were therefore defined both for the skin and the adipose tissues to account for this local stiffening. For both tissues, the  $C_{10}$  coefficient was multiplied by 1, 1.5 or 2 for the areas nearest to the wound [27] to define soft, medium and rigid material, respectively.





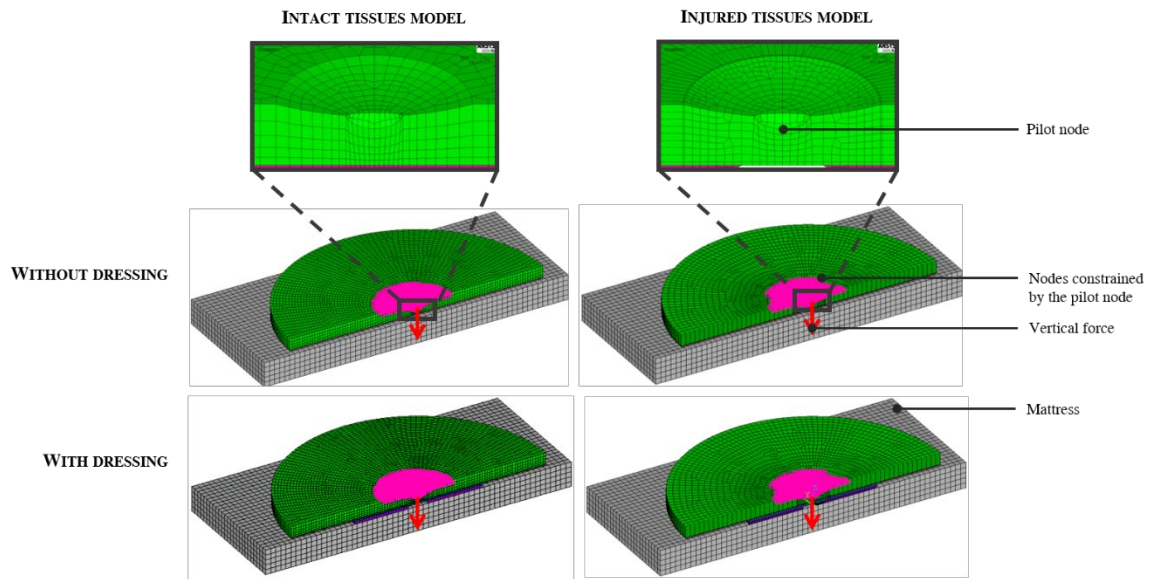
82

83 *Figure 4: Models of the dressing/soft tissues coupling with intact (top) and injured soft-tissues (bottom).*

84 **2.2.4. Boundary conditions and loading**

85 Nodes between skin and adipose tissue, skin and “dressing layer 2”, and, between “dressing layer 2” and  
 86 “dressing layer 1”, were tied (Figure 5). Friction tests were performed to assess the coefficient of friction between  
 87 the support and the dressing layer 2, set to 0.62. A coefficient of friction of 0.43 was set between the skin and the  
 88 mattress [29].

89 A vertical force of 47 % of the subject body weight was simulated, to account for the weights of thighs,  
 90 pelvis and abdomen body segments [28]. Considering the symmetry of the model, half of the resulting force, 217  
 91 N, was applied to a pilot node, located at the center of the bony prominence. All nodes at the boundary between  
 92 the sacrum and the adipose tissues, in a radius of 68.5 mm, were tied in displacement with the pilot node. This  
 93 radius was equal to half the distance between the sacroiliac crests measured on the sacrum 3D reconstruction of  
 94 the volunteer (Figure 5). The bottom nodes of the mattress were fixed.



95

96  
97

Figure 5: Models of the dressing interaction with intact (left) and injured (right) tissues. Pink areas represent the nodes tied to the pilot node.

98

## 2.3. Model validation

99

### 2.3.1. Experimental setup

100

101

102

103

104

105

106

107

108

The volunteer was wearing tights and laid in supine position on a rigid support, holding his legs up to exacerbate the loading on the sacrum to account for a worst-case scenario. A Tekscan 5250 pressure sensor (Tekscan, South Boston, USA) with 44x44 sensors was positioned between the rigid support and the sacral region. The calibration was performed according to the manufacturer protocol. The sensor could measure pressures up to 1 724 kPa with a 5 mm resolution. Three acquisitions of 30 s were recorded for all configurations. First measurements were performed without the dressing. Pressures were then measured with the dressing placed between the rigid support and the pressure sensor (Figure 6, left panel). For such a case, the alveoli located at the position of the previously measured peak pressure were removed.

109

110

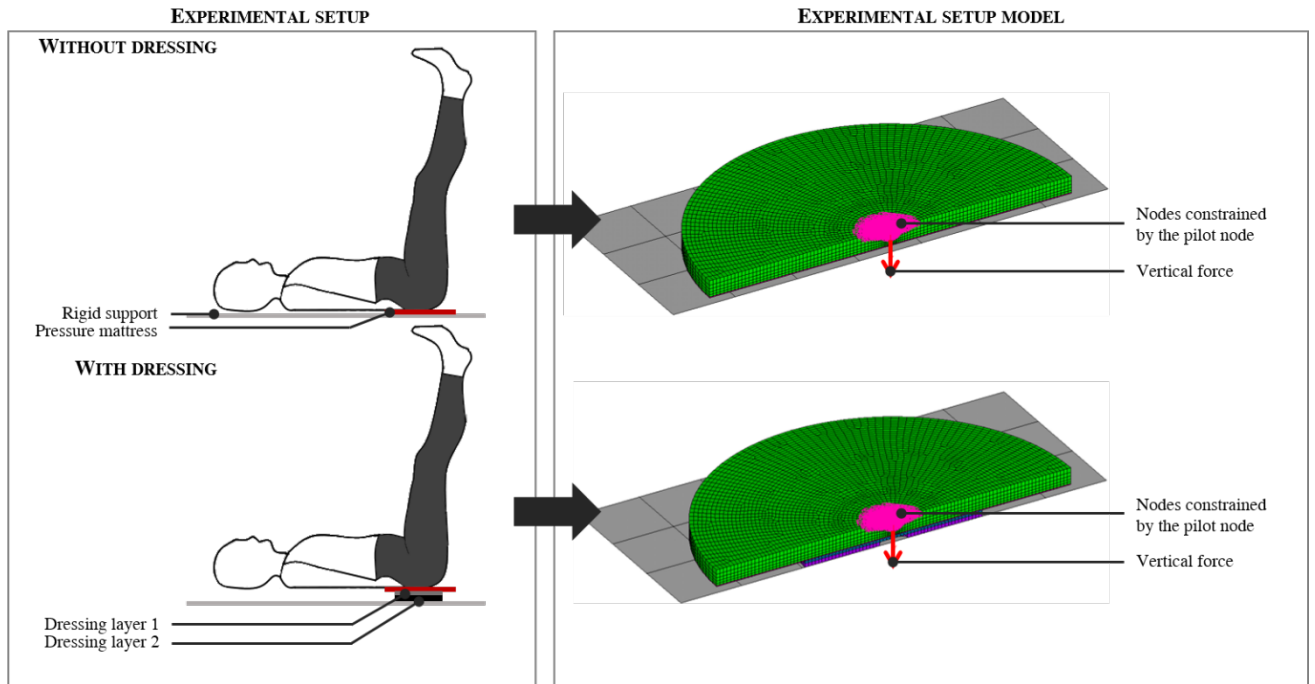
111

112

*2.3.2. Experimental setup model*

The intact tissues model was used for the evaluation. Yet loads were adapted to the performed experiments (Figure 6, right panel). Since the experiment aimed to load solely the sacrum prominences, only nodes in a radius of 37 mm around center of the model were tied to the pilot node. Because of the symmetry in the model, half the forces measured during the experiments without and with the dressing, respectively 291 N and 245 N, were applied

113 to the pilot node as vertical forces. Considering the experimental setup, the subject was simulated as lying on a  
114 rigid support.



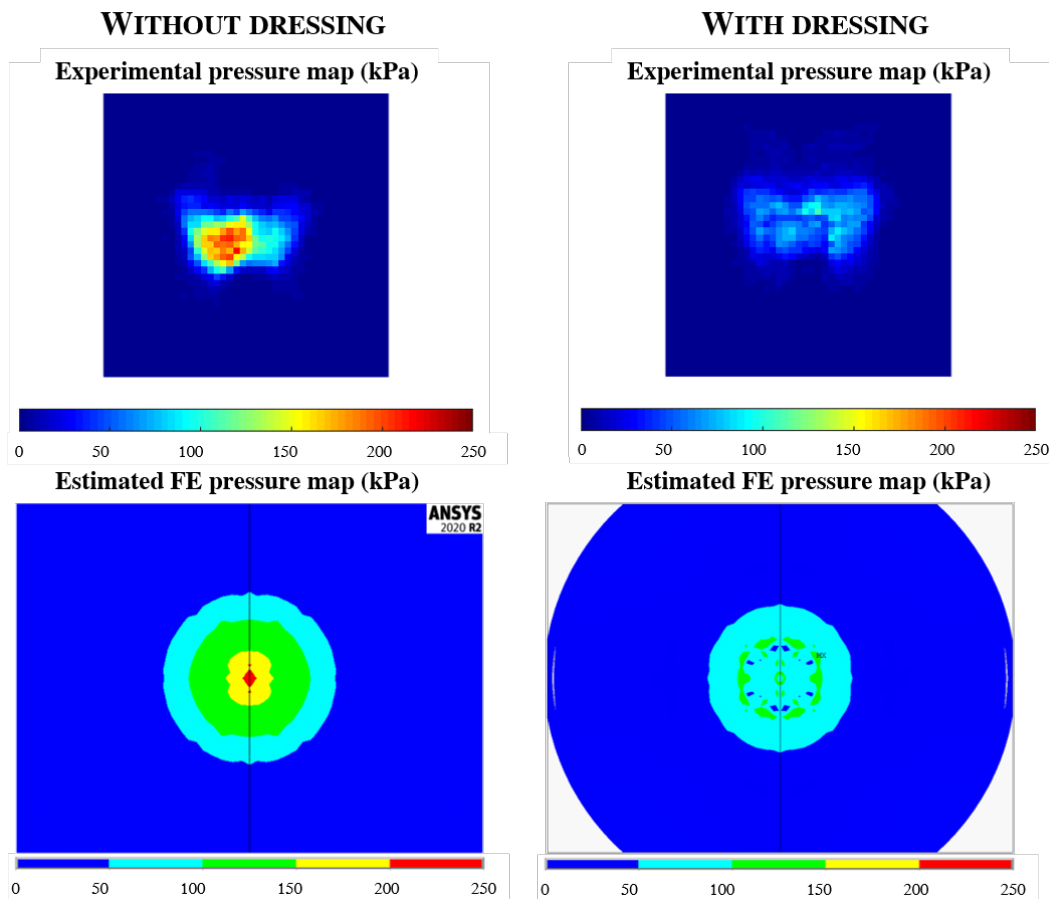
115

116 *Figure 6: Experimental setup (left) and associated models (right) without (top) and with (bottom) the dressing. Pink*  
117 *areas represent the nodes tied to the pilot node. Pressure sensor and dressing thicknesses were exaggerated for*  
118 *illustration*

# 119 3. Results

## 120 3.1. Pressure estimations

121 To account for the soft tissues conditioning during the trials, the mean pressures measured for the last  
122 acquisition of both experiments were used to validate the model. Pressure measurements without and with the  
123 dressing are shown in Figure 7. Peak pressures measured during the experiment were 218 kPa without the dressing  
124 and 126 kPa with the dressing. Peak pressures estimated by the FE model without the dressing was located at the  
125 center of the skin interface and was up to 217 kPa. With the model that includes the dressing, maximal pressures  
126 were estimated up to 147 kPa and were located at the level of opened alveoli boundary, while the simulated  
127 maximal pressure at the center of the model were equal to 102 kPa.

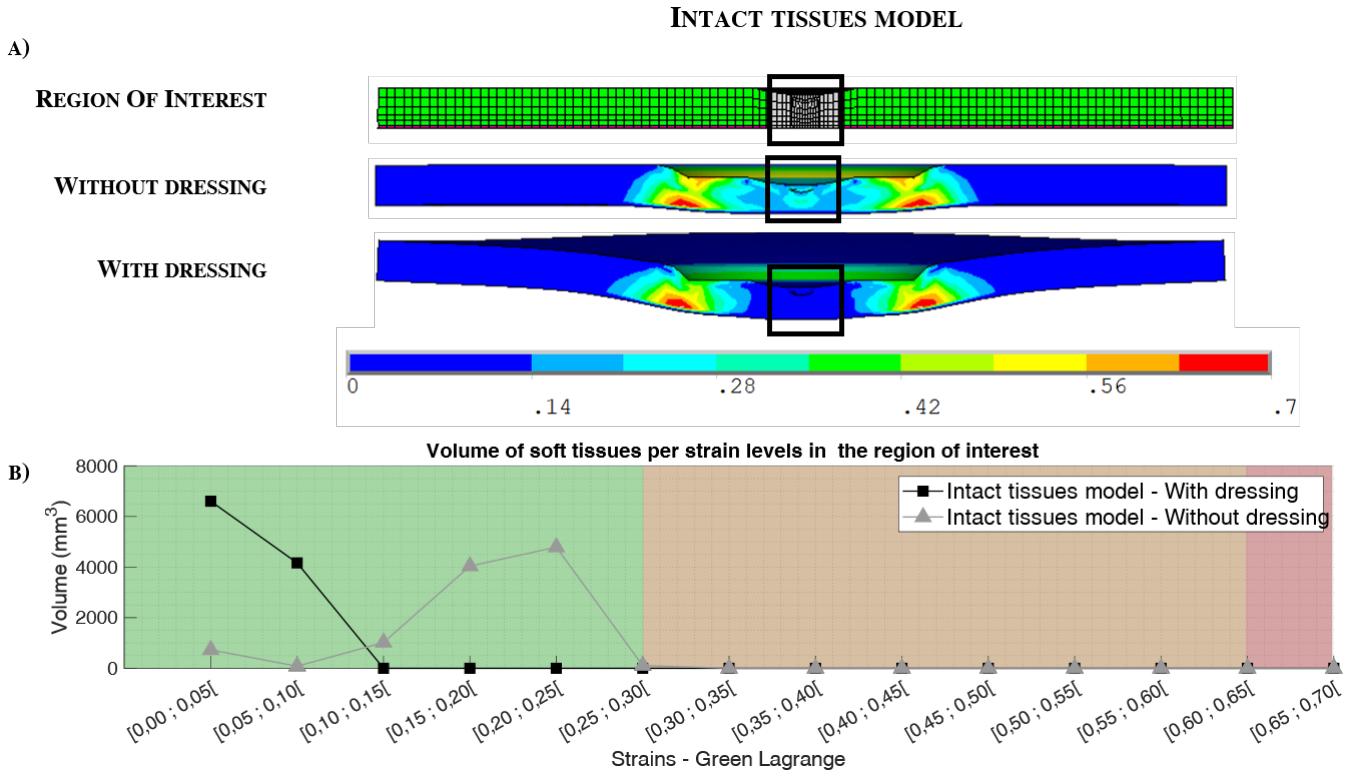


128  
129 *Figure 7: Pressure measurements (top) and estimations (bottom) obtained without (left) and with (right) dressing.*

## 130 3.2. Internal strains with the intact tissues model

131 Green-Lagrange maximal shear strains are assumed to be a relevant numerical biomarker for PU  
132 prevention [4] and were computed from the simulations. The Region Of Interest (ROI) consisted of all soft tissues

133 elements included in a radius lower than 19.5 mm. This value included the soft tissues below the surface  
 134 surrounding the bony prominence where strains should be as low as possible according to clinician experts. The  
 135 dressing helped to decrease the internal strains in the ROI. The volumes of soft tissues above strains thresholds are  
 136 presented in Figure 8. The peak strain in the ROI was estimated to 0.42 without dressing. This value decreased to  
 137 0.23 with the dressing.



138

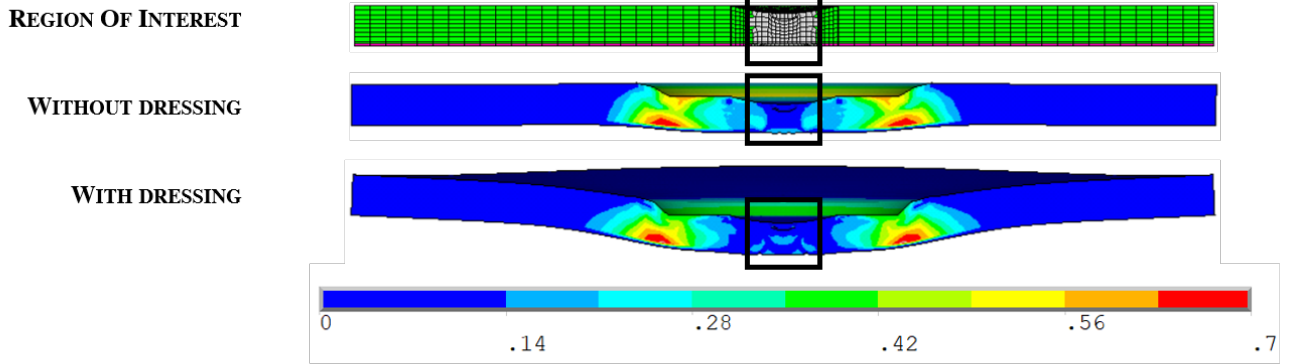
139 *Figure 8: A) Strains in the sagittal plane. The dark square circled the ROI. B) Volume of soft tissues in ranges of strains for*  
 140 *the intact tissues model without (grey triangles) and with the dressing (black squares) in the ROI. Green, orange and red*  
 141 *regions are safe, potentially injurious and injurious domains of strains respectively [4].*

### 142 3.3. Internal strains with the injured tissues model

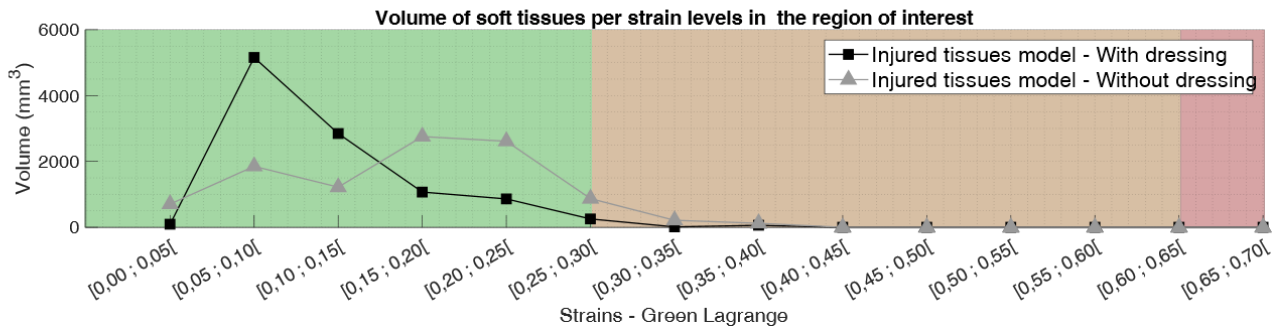
143 Assuming a category-2 PU developed, the dressing was also able to reduce the internal strains (Figure 9)  
 144 in the ROI. The peak strain was estimated to 0.43 without dressing, and decreased to 0.30 with the dressing.

### INJURED TISSUES MODEL

A)



B)



145

146

147

148

149

Figure 9: A) Strains in the sagittal plane. The dark square circled the ROI. B) Volume of soft tissues in ranges of strains for the injured tissues model without (grey triangles) and with the dressing (black squares) in the ROI. Green, orange and red regions are safe, potentially injurious and injurious domains of strains respectively [4].

## 150 **4. Discussion**

151 This study focused on a new approach based on a parametric model of the sacral area, interacting with a  
152 new dressing developed by Urgo RID, to investigate internal strains in the context of PU prevention. Thus, the FE  
153 method was used to model intact and injured tissues. To evaluate the model, one volunteer participated to  
154 measurements of pressures at the interface between the sacral region and the dressing, in a worst-case scenario.  
155 These measures were compared to the pressure estimated with the model.

156 FE estimations of the pressure showed a good agreement with measurements with and without the  
157 dressing. Yet estimated peak pressures, up to 217 kPa, revealed an overloading of the tissues during the experiment.  
158 This was performed on purpose to account for the worst-case scenario. In fact, clinical pressures as measured at  
159 the interface with the sacral areas do not exceed 15 kPa [30,31]. Peak pressure estimations were close to the  
160 measured pressure with an error up to 24 kPa. Errors may be explained by numerical geometrical non-linearities  
161 at the dressing boundary and also by the resolution of the pressure sensor, that may not capture local extrema.  
162 Internal strains were also estimated with and without the dressing. Loadings was modified to assess clinically  
163 relevant internal strains. As expected, the presence of the dressing resulted in a decrease of the soft tissues strains  
164 in intact tissues surrounding the bony prominence. The reduction of the peak strain by 45 %, highlighted the  
165 prophylactic effect of the dressing like in other literature studies [7,14,18,32]. Yet, this study focuses on a new  
166 dressing based on the combination with a honeycombed deformable layer. Considering injured soft tissues with a  
167 category-2 PU, results showed a decrease of the internal strains surrounding the PU with a reduction of the peak  
168 strain by 30 %. To our knowledge, this study is the first attempt to numerically investigate the ability of a dressing  
169 to reduce strains of category-2 sacral PU. A similar attempt was proposed for category-4 PU [18] and showed also  
170 a benefit of the dressings on the internal stresses. Direct comparison between both models was not possible since,  
171 in the present study, soft tissues were modelled between the bone and the wound bottom. To our knowledge, no  
172 other literature studies provided internal strains data in the human sacral area when lying on a rigid surface.

173 Some limitations may impact these findings. The parametric approach involved a simplification of the  
174 geometry that may lack accuracy to estimate isolated stress/strain concentration areas. Some parameters of the  
175 models had to be defined arbitrarily since they could not be measured such as the Poisson's ratio for soft tissues.  
176 A preliminary study revealed that this coefficient could be set between 0.4999 and 0.499 to account for a soft  
177 tissues' volume change from 2 % to 18 % respectively. The impact of this parameter on the results of the simulation  
178 clearly indicates that further investigation should be conducted to evaluate its value. It is however important to

179 mention that the efficacy of the dressing is still satisfying if the Poisson's ratio is changed to 0.499. In addition,  
180 the duration of the loading was not investigated [33]. The time parameter may, however, be implemented in further  
181 work since tissues and dressings may have viscoelastic properties. The time parameter may also be modelled to  
182 consider the biochemical and biophysical phenomenon that were not studied here such as the inflammation or  
183 ischemia [3]. Further work may also focus on the implementation of clinical parameters such as the head-of-bed  
184 elevation and the use of a mattress to assess the efficacy of the dressing in a clinical environment [12] but also  
185 extend this work to more subjects to account for geometrical but also material properties discrepancies in different  
186 populations. Finally, this model provided results applicable to category-2 PU and may not be extended to deeper  
187 wounds as this should involve further developments.

188           Eventually, this study highlights the potential of a new dressing which may benefit the PU healing process  
189 an also act as a prophylactic device with the implementation of a FE model. The FE method allows scientists,  
190 industry partners and clinicians, to assess data such as the internal strains that cannot be measured *in vivo* but are  
191 still fundamental to evaluate the risk of development of a PU.

192



## 193 5. Acknowledgement

194

## 195 6. Conflict of interest

196 This study was supported by Urgo RID.

## 197 7. References

- 198 [1] L. Demarré, A. Van Lancker, A. Van Hecke, S. Verhaeghe, M. Grypdonck, J. Lemey, L. Annemans, D.  
199 Beeckman, The cost of prevention and treatment of pressure ulcers: A systematic review, *Int. J. Nurs.*  
200 *Stud.* 52 (2015) 1754–1774. <https://doi.org/10.1016/j.ijnurstu.2015.06.006>.
- 201 [2] S.S. Loerakker, A. Stekelenburg, G.J. Strijkers, J.J.M. Rijkema, F.P.T. Baaijens, D.L. Bader, K.  
202 Nicolay, C.W.J. Oomens, Temporal effects of mechanical loading on deformation-induced damage in  
203 skeletal muscle tissue, *Ann. Biomed. Eng.* 38 (2010) 2577–2587. [https://doi.org/10.1007/s10439-010-](https://doi.org/10.1007/s10439-010-0002-x)  
204 [0002-x](https://doi.org/10.1007/s10439-010-0002-x).
- 205 [3] A. Gefen, D.M. Brienza, J. Cuddigan, E. Haesler, J. Kottner, Our contemporary understanding of the  
206 aetiology of pressure ulcers/pressure injuries, *Int. Wound J.* (2021) 1–13.  
207 <https://doi.org/10.1111/iwj.13667>.
- 208 [4] K.K. Ceelen, A. Stekelenburg, S. Loerakker, G.J. Strijkers, D.L. Bader, K. Nicolay, F.P.T. Baaijens,  
209 C.W.J. Oomens, Compression-induced damage and internal tissue strains are related, 41 (2008) 3399–  
210 3404. <https://doi.org/10.1016/j.jbiomech.2008.09.016>.
- 211 [5] C.V.C. Bouten, M.M. Knight, D.A. Lee, D.L. Bader, Compressive deformation and damage of muscle  
212 cell subpopulations in a model system, *Ann. Biomed. Eng.* 29 (2001) 153–163.  
213 <https://doi.org/10.1114/1.1349698>.
- 214 [6] C.W.J. Oomens, O.F.J.T. Bressers, E.M.H. Bosboom, C.V.C. Bouten, D.L. Bader, Can loaded interface  
215 characteristics influence strain distributions in muscle adjacent to bony prominences?, *Comput. Methods*  
216 *Biomech. Biomed. Engin.* 6 (2003) 171–180. <https://doi.org/10.1080/1025584031000121034>.
- 217 [7] R. Walker, L.M. Aitken, L. Huxley, M. Juttner, Prophylactic dressing to minimize sacral pressure  
218 injuries in high-risk hospitalized patients: A pilot study, *J. Adv. Nurs.* 71 (2015) 688–696.  
219 <https://doi.org/10.1111/jan.12543>.

- 220 [8] S.K. Miller, N. Sharma, L.C. Aberegg, K.N. Blasiolo, J.A. Fulton, Analysis of the Pressure Distribution  
221 Qualities of a Silicone Border Foam Dressing, *J. Wound, Ostomy Cont. Nurs.* 42 (2015) 346–351.  
222 <https://doi.org/10.1097/WON.000000000000130>.
- 223 [9] K.K. Ceelen, A. Stekelenburg, J.L.J. Mulders, G.J. Strijkers, F.P.T. Baaijens, K. Nicolay, C.W.J.  
224 Oomens, Validation of a numerical model of skeletal muscle compression with MR tagging: A  
225 contribution to pressure ulcer research, *J. Biomech. Eng.* 130 (2008) 1–8.  
226 <https://doi.org/10.1115/1.2987877>.
- 227 [10] L. Peko Cohen, Z. Ovadia-Blechman, O. Hoffer, A. Gefen, Dressings cut to shape alleviate facial tissue  
228 loads while using an oxygen mask, *Int. Wound J.* 16 (2019) 813–826. <https://doi.org/10.1111/iwj.13101>.
- 229 [11] A. Gefen, Pressure ulcer prevention dressing design and biomechanical efficacy, *J. Wound Care.* 29  
230 (2020) S6–S15. <https://doi.org/10.12968/jowc.2020.29.Sup12.S6>.
- 231 [12] M. Lustig, N. Wiggermann, A. Gefen, How patient migration in bed affects the sacral soft tissue loading  
232 and thereby the risk for a hospital-acquired pressure injury, *Int. Wound J.* 17 (2020) 631–640.  
233 <https://doi.org/10.1111/iwj.13316>.
- 234 [13] B.W.S. Soh, A. Corrias, L. Tucker-Kellogg, Computational modeling of the thin muscle layer,  
235 panniculus carnosus, demonstrates principles of pressure injury and prophylactic dressings, Elsevier Inc.,  
236 2019. <https://doi.org/10.1016/B978-0-12-815028-3.00003-1>.
- 237 [14] J. Sieracki, R. Wilkes, E.R. Bennett, A.K. McNulty, Finite Element Analysis Modeling of a Novel  
238 Silicone Dressing, *Cureus.* 12 (2020). <https://doi.org/10.7759/cureus.10629>.
- 239 [15] D. Schwartz, A. Levy, A. Gefen, A Computer Modeling Study to Assess the Durability of Prophylactic  
240 Dressings Subjected to Moisture in Biomechanical Pressure Injury Prevention, *Ostomy Wound Manag.*  
241 64 (2018) 18–26. <https://doi.org/10.25270/owm.2018.7.1826>.
- 242 [16] A. Levy, A. Gefen, Assessment of the Biomechanical Effects of Prophylactic Sacral Dressings on Tissue  
243 Loads: A Computational Modeling Analysis, *Ostomy Wound Manag.* 63 (2017) 48–55.  
244 <https://doi.org/10.25270/owm.10.4855>.
- 245 [17] B.E. Keenan, S.L. Evans, C.W.J. Oomens, A review of foot finite element modelling for pressure ulcer  
246 prevention in bedrest: Current perspectives and future recommendations, *J. Tissue Viability.* (2021).  
247 <https://doi.org/10.1016/j.jtv.2021.06.004>.
- 248 [18] D. Schwartz, A. Gefen, The biomechanical protective effects of a treatment dressing on the soft tissues  
249 surrounding a non-offloaded sacral pressure ulcer, *Int. Wound J.* 16 (2019) 684–695.

- 250 <https://doi.org/10.1111/iwj.13082>.
- 251 [19] W. Lee, B.H. Won, S.W. Cho, Finite element modeling for predicting the contact pressure between a  
252 foam mattress and the human body in a supine position, *Comput. Methods Biomech. Biomed. Engin.* 20  
253 (2017) 104–117. <https://doi.org/10.1080/10255842.2016.1203421>.
- 254 [20] A. Isihara, N. Hashitsume, M. Tatibana, Statistical theory of rubber-like elasticity. IV. (Two-dimensional  
255 stretching), *J. Chem. Phys.* 19 (1951) 1508–1512. <https://doi.org/10.1063/1.1748111>.
- 256 [21] A. Ní Annaidh, K. Bruyère, M. Destrade, M.D. Gilchrist, M. Otténio, Characterization of the anisotropic  
257 mechanical properties of excised human skin, *J. Mech. Behav. Biomed. Mater.* 5 (2012) 139–148.  
258 <https://doi.org/10.1016/j.jmbbm.2011.08.016>.
- 259 [22] O.H. Yeoh, Characterization of Elastic Properties of Carbon-Black-Filled Rubber Vulcanizates, *Rubber  
260 Chem. Technol.* 63 (1990) 792–805. <https://doi.org/10.5254/1.3538289>.
- 261 [23] G. Sommer, M. Eder, L. Kovacs, H. Pathak, L. Bonitz, C. Mueller, P. Regitnig, G.A. Holzapfel,  
262 Multiaxial mechanical properties and constitutive modeling of human adipose tissue: A basis for  
263 preoperative simulations in plastic and reconstructive surgery, *Acta Biomater.* 9 (2013) 9036–9048.  
264 <https://doi.org/10.1016/j.actbio.2013.06.011>.
- 265 [24] P.H. Mott, J.R. Dorgan, C.M. Roland, The bulk modulus and Poisson’s ratio of “incompressible”  
266 materials, *J. Sound Vib.* 312 (2008) 572–575. <https://doi.org/10.1016/j.jsv.2008.01.026>.
- 267 [25] M. Sato, H. Sanada, C. Konya, J. Sugama, G. Nakagami, Prognosis of stage I pressure ulcers and related  
268 factors, *Int. Wound J.* 3 (2006) 355–362. <https://doi.org/10.1111/j.1742-481X.2006.00267.x>.
- 269 [26] L. Agam, A. Gefen, Pressure ulcers and deep tissue injury in wheelchair users: A bioengineering  
270 perspective, *Int. J. Ther. Rehabil.* 15 (2008) 90–99. <https://doi.org/10.12968/ijtr.2008.15.2.28192>.
- 271 [27] L.E. Edsberg, R. Cutway, S. Anain, J.R. Natiella, Microstructural and mechanical characterization of  
272 human tissue at and adjacent to pressure ulcers, *J. Rehabil. Res. Dev.* 37 (2000) 463–471.
- 273 [28] S. Plagenhoef, F.G. Evans, T. Abdelnour, *Anatomical Data for Analyzing Human Motion* University of  
274 Massachusetts -Amherst, *Res. Q. Exerc. Sport.* 54 (1983) 169–178.
- 275 [29] E. Call, J. Pedersen, B. Bill, J. Black, P. Alves, C.T. Brindle, C. Dealey, N. Santamaria, M. Clark,  
276 Enhancing pressure ulcer prevention using wound dressings: What are the modes of action?, *Int. Wound  
277 J.* 12 (2015) 408–413. <https://doi.org/10.1111/iwj.12123>.
- 278 [30] D.L. Bader, P.R. Worsley, A. Gefen, Bioengineering considerations in the prevention of medical device-  
279 related pressure ulcers, *Clin. Biomech.* 67 (2019) 70–77.

- 280 <https://doi.org/10.1016/j.clinbiomech.2019.04.018>.
- 281 [31] T. Defloor, The effect of position and mattress on interface pressure., *Appl. Nurs. Res.* 13 (2000) 2–11.
- 282 [https://doi.org/10.1016/S0897-1897\(00\)80013-0](https://doi.org/10.1016/S0897-1897(00)80013-0).
- 283 [32] L. Peko Cohen, A. Levy, N. Shabshin, Z. Neeman, A. Gefen, Sacral Soft Tissue Deformations When
- 284 Using a Prophylactic Multilayer Dressing and Positioning System: MRI Studies, *J. Wound, Ostomy,*
- 285 *Cont. Nurs. Off. Publ. Wound, Ostomy Cont. Nurses Soc.* 45 (2018) 432–437.
- 286 <https://doi.org/10.1097/WON.0000000000000461>.
- 287 [33] A. Gefen, B. van Nierop, D.L. Bader, C.W.J. Oomens, Strain-time cell-death threshold for skeletal
- 288 muscle in a tissue-engineered model system for deep tissue injury, *J. Biomech.* 41 (2008) 2003–2012.
- 289 <https://doi.org/10.1016/j.jbiomech.2008.03.039>.
- 290