Modelling quasi-incompressibility of soft-tissues to quantify strains for pressure ulcers healing

N. Fougeron[a], N. Connesson[a], G. Chagnon[a], T. Alonso[a], L. Pasquinet[c], M. Bahuon[c], E. Guillin[c], A. Perrier[a,b] and Y. Payan[a]

[a]Univ. Grenoble Alpes, CNRS, UMR 5525, VetAgro Sup, Grenoble INP, TIMC, Grenoble, France; [b]Service de Diabétologie, AP-HP, Paris, France; [c]Urgo Research, Innovation & Development, Chenôve, France

1. Introduction

A Pressure Ulcer (PU) is a skin wound that may propagate to underlying tissues. PU mostly develop under bony prominences when skin is in interaction with external supports or medical devices. Up to 23% of patients in healthcare facilities may suffer from PU (Demarré et al. 2015). Dressings may be used to guarantee a favourable biochemical and biophysiological environment to heal the wound. However, very few attempts were proposed to evaluate their mechanical impact on soft tissues. In fact, they may alter the strains in the PU area, yet, excessive strains may lead to damage of the surrounding tissues. Indeed, Green-Lagrange (GL) shear strains were pointed out as a good biomarker to predict the onset of PU (Ceelen et al. 2008). Such strains can be estimated via patient-specific Finite Element Modelling (FEM). To the authors' knowledge, only Schwartz and Gefen (2019) proposed a FEM of a category-4 PU to highlight the efficacy of dressings to protect tissues. However, the material properties proposed by these authors to model the behaviour of soft tissues were set according to animal testing. Moreover, the Poisson's ratio was set arbitrarily to $\nu = 0.49$ to account for the nearly incompressible behaviour of soft tissues. If the Poisson's ratio can be up to $\nu = 0.495$ in FEM models of soft tissues (Dickinson et al. 2017; Keenan et al. 2021), the validation of this hypothesis is still lacking. Indeed, when $\nu = 0.495$, the resulting ratio of bulk to shear modulus, κ/μ, is far from the recommendation of Bonet and Wood (2008) who suggested κ/μ should be over 10^3 to model nearly-incompressible solids. The aim of the present study is to evaluate the impact of the Poisson's ratio on the GL shear strains in a FEM of the interaction of a sacral PU and a dressing.

2. Methods

2.1. FEM

A parametric FEM including the adipose tissues, the skin, a new bi-layer PU dressing designed by Urgo RID and a mattress was developed for this study (Figure 1). The bone boundary was simplified to represent a bony prominence on the sacrum. A 3.2 mm deep PU was added to the model at the skin surface located under the bony prominence. Soft tissues thickness and bone dimensions were extracted from ultrasound images of one healthy volunteer. The PU dressing model was set according to the geometrical specifications provided by Urgo RID. No sliding was allowed between the model's components except at the interface between the mattress and the dressing with a coefficient of friction set to 0.62 according to experimental measurements. The bottom nodes of the mattress were fixed while a vertical force of 443 N, equivalent to 47% of the volunteer bodyweight, was imposed to the nodes at the bone boundary. The quasi-static analyses were performed on Ansys MAPDL, using an implicit scheme.

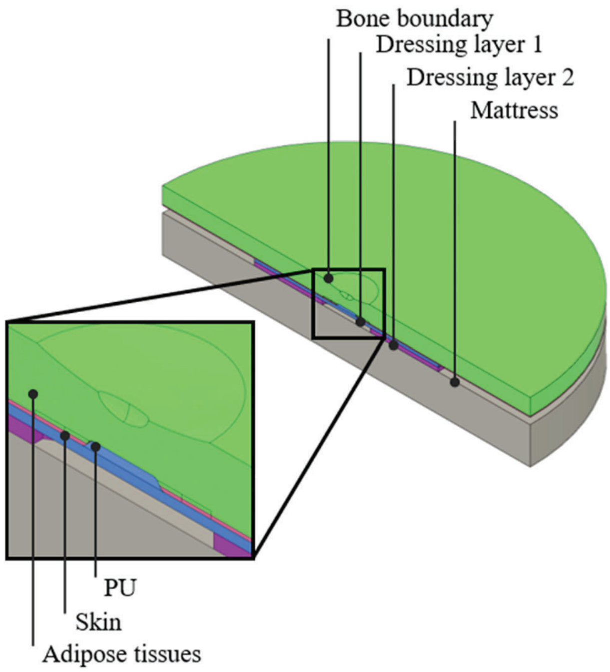

Figure 1. Model of soft-tissues with a PU and the bi-layer dressing.

2.2. Material characterisation

Hyperelastic constitutive equations were set for soft tissues with a curve fitting method based on literature experimental data (Annaidh et al. 2012; Sommer et al. 2013). The dressing first layer was modelled as an orthotropic linear elastic compress whereas the second layer was a compressible honeycombed solid. Both models' parameters were set according to tension and compression tests using a curve fitting approach. The

Table 1. Material parameters.

Layer	Model	Moduli (kPa)	Poisson's ratio
Adipose tissue	Yeoh	$C_{10} = 0.1$ $C_{20} = 0.0$ $C_{30} = 12.2$	[0.4950; 0.4999]
Skin	Isihara	$C_{10} = 270$ $C_{20} = 1900$	[0.4950; 0.4999]
Dressing layer 1	Linear elastic	$E_x = 4400$ $E_y = 1800$	0.256
Dressing layer 2	Blatz-Ko	$\mu = 1.0$	–
Mattress	Linear elastic	$E = 230$	0.3

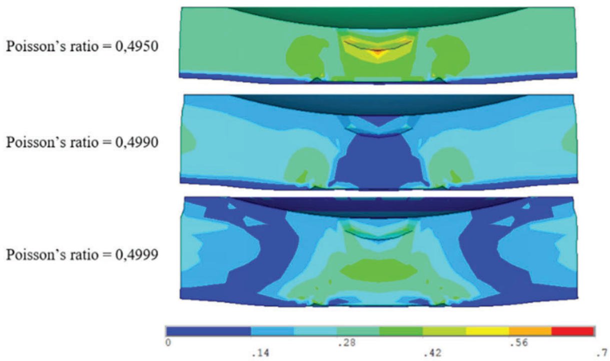

Figure 2. GL shear strains in the PU area with Poisson's ratio of 0.4950 (top), 0.4990 (middle) and 0.4999 (bottom).

mattress was modelled as a linear elastic material as suggested by Lee et al. (2017). Materials' details are provided in Table 1.

2.3. Soft tissues Poisson's ratio sensitivity

The Poisson's ratio, ν, was set to 0.4950, 0.4990, and 0.4999 to evaluate its impact on the quantity of healthy tissues in the PU area. These values were equivalent to a ratio of bulk to shear modulus, κ/μ, of approximately 100, 500 and 5000 (Love 1892). Healthy tissues were arbitrarily defined as those deformed under a threshold of 30% of GL shear strains (Ceelen et al. 2008).

3. Results and discussion

Percentage of healthy tissues to the total volume of tissues were 7%, 95% and 94% and the peak GL shear strains were 64%, 46% and 52%, respectively, for a Poisson's ratio of 0.4950, 0.4990 and 0.4999. Differences in the pattern of GL strains in the PU area are presented in Figure 2.

Surprisingly, strains turned out to be very sensitive to small changes in the Poisson's ratio. This is similar to the results of Vannah and Childress (1993) who performed 2D FEM of the internal stresses.

4. Conclusions

This study highlighted the impact of the Poisson's ratio on the results on the GL shear strains. This issue is all the more complex because the Poisson's ratio of living tissues is tedious to assess *in vivo*. However, the results stress out that modelling hypotheses on the level of incompressibility could completely change the conclusion regarding the soft tissues integrity.

Acknowledgement

The authors would like to thank Urgo RID for their financial support.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

Urgo RID

References

Annaidh AN, Karine Bruyère, Destrade M, Gilchrist MD, Maurini C, Otténio M, Saccomandi G. 2012. Automated estimation of collagen fibre dispersion in the dermis and its contribution to the anisotropic behaviour of skin. Ann Biomed Eng. 40(8):1666–1678.

Bonet J, Wood RD. 2008. Nonlinear continuum mechanics for finite element analysis, 2nd ed. Cambridge: Cambridge University Press.

Ceelen KK, Stekelenburg A, Loerakker S, Strijkers GJ, Bader DL, Nicolay K, Baaijens FPT, Oomens CWJ. 2008. Compression-induced damage and internal tissue strains are related. 41:3399–3404.

Demarré L, Van Lancker A, Van Hecke A, Verhaeghe S, Grypdonck M, Lemey J, Annemans L, Beeckman D. 2015. The cost of prevention and treatment of pressure ulcers: a systematic review. Int J Nurs Stud. 52(11): 1754–1774.

Dickinson AS, Steer JW, Worsley PR. 2017. Finite element analysis of the amputated lower limb: A systematic review and recommendations. Med Eng Phys. 43: 1–18.

Keenan BE, Evans SL, Oomens CWJ. 2021. A review of foot finite element modelling for pressure ulcer prevention in bedrest: current perspectives and future recommendations. J Tissue Viability. 31(1):73–83

Lee W, Won BH, Cho SW. 2017. Finite element modeling for predicting the contact pressure between a foam mattress and the human body in a supine position. Comput Method Biomech Biomed Eng. 20(1):104–117.

Love AM. 1892. A treatise on the mathematical theory of elasticity. Cambridge: Cambridge University Press.

Schwartz D, Gefen A. 2019. The biomechanical protective effects of a treatment dressing on the soft tissues surrounding a non-offloaded sacral pressure ulcer. Int Wound J. 16(3):684–695.

Sommer G, Eder M, Kovacs L, Pathak H, Bonitz L, Mueller C, Regitnig P, Holzapfel GA. 2013. Multiaxial mechanical properties and constitutive modeling of human adipose tissue: A basis for preoperative simulations in plastic and reconstructive surgery. Acta Biomater. 9(11):9036–9048.

Vannah WM, Childress DS. 1993. Modelling the mechanics of narrowly contained soft tissues: The effects of specification of Poisson's ratio. J Rehabil Res Dev. 30(2):205–209.

KEYWORDS Incompressibility; pressure ulcers; soft tissues; finite element modelling; Poisson's ratio

Nolwenn.fougeron@univ-grenoble-alpes.fr