Modeling and Experimental of the Mechanical Behavior of Seat Cushion for Wheelchair Users

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Abstract. The cushions assistance to the pressure ulcers (PUs) prevention has like objective to improve wheelchair users by decreasing the effects of pressure between the both surfaces. Innovating honeycomb cushion (HC) containing thermoplastic polyurethane (TPU) which has many advantages was studied using a biomechanical and digital model for simulation. We used the finite element method (FEM) for the cushion simulation and modelization. This method led to the structural decomposition of the cushion in the aim to evaluate his mechanical behavior. This comportment was simulated numerically by FEM on cell of the cushion, then on the whole cushion. The tests of compression carried out with the electromechanical press (INSTRON 33R4204 machine) on HC permitted to determine curves related to his mechanical behavior. The result helps the comparison with the numerical model developed in this study. This result permits to study the distribution of pressure, shearing, friction and the microclimate which are sources of PUs through HC. The idea following this work is to optimize the HC in the aim to present a new product satisfying the needs for wheelchair users. The design of HC for prevention assistance of the scabs in only one layer is possible and present many advantages: optimization of the manufacturing process, improved ventilation, facilitated cleaning and decreasing cost.

1. Introduction
The pressure ulcers (PUs) is a localized injury to the skin and/or underlying tissue usually located over a bony prominence. In general, this lesion results from a pressure due to a compression effect and/or shear. Many contributing or confounding factors are also associated with pressure ulcers. It has been estimated that 90% of pressure ulcers occur at the contact between the buttock-tissue and the seat cushion. For people who use a wheelchair, the pressure ulcer often occurs in regions of the ischial, sacrum and the greater trochanter of the femur [1]. There are many ways to prevent pressure ulcer for improving seated comfort and reducing pressure ulcers for wheelchair users. The average cost of treatment was estimated in the United Kingdom (UK) according to the stages of disease severity. The ranges are from 1,200 € for a simple redness to 12,500 € for fourth stage that the depth of the wound is large and frequent infectious complications [2]. The pressure leads to pressure ulcers resulting in tissue hypoxia, which is defined as deprived of adequate oxygen supply in subcutaneous tissues. The reduction of blood supply and oxygen is mainly due to excessive pressure that would of blood vessels and leads to ischemia [3]. It is well-known that the movements appear mainly in the sagittal plane compared to the frontal plane [4]; a position change is required in spinal cord injury patients to relieve discomfort in subcutaneous tissues.
On the viewpoint of clinical medicine, the pressure ulcer mainly depends on several intrinsic and extrinsic factors. The intrinsic factors are attributed, among others, malnutrition, aging, obesity, incontinence, dry skin, muscles atrophy, poor posture and immobility. The extrinsic factors themselves are rather due to pressure, shear, friction and microclimate of the skin [1, 5, 6]. These extrinsic factors are the most important factor [7] and return to the patient's comfort and the idea of a welfare related to a particular seat position [8]. The comfort is a personal and subjective notion. It is comfortable for one, will not be necessarily for another. For example, people with smaller muscles, less resistant to deformation of tissue and it is easily, therefore, to be discomfort and tissue damage [9]. The weight is obviously considered and the Body Mass Index (BMI) of a person is calculated are greater than the increase of the pressure on the cushion [10-11]. The pressure distribution on cushions reduces the pressure ulcers. These studies were performed on paraplegic subjects, neurological, elderly and disabled, to observe the influence of the medium pressure. The high pressure, or the lower contact surface, while paraplegics have high-pressure peaks more than valid [12]. Furthermore, other studies to evaluate the relationship between the perception of seating comfort on a cushion and the interface pressure, the temperature and humidity have been conducted on wheelchair users. The results showed that the comfort was not necessarily related to the interface pressures, weak or important. In addition, the discomfort was not necessarily related to the highest temperatures [7, 13]. It should be noted that users seem to privilege with a medium-firm level of cushion properties. The time factor strongly influences the feeling of comfort and can leads to fatigue. One static position for many hours, compress the tissues of the buttocks area and will be perceived as very unpleasant [9]. There are several interacting factors influence to the comfort [9]: (i) poor distribution of stresses in the soft tissue, (ii) the accumulation of moisture, (iii) the accumulation or heat loss, (iv) less stability. The aim of this study is to investigate the mechanical behavior of seat in a wheelchair, especially on a Stimulite cushion thermoplastic polyurethane honeycomb (TPU). The research presents many advantages compared to other previous studies.

2. Cushion Modeling

2.1. Spatial Geometry and CAD model
The objective is to model and numerically simulate the mechanical behavior of a Stimulite honeycomb cushion composed of thousands of flexible cells (Figure 1) and these numerical results from simulation are compared with those of experimental tests.

![Stimulite honeycomb cushion](image.png)

Figure 1. Stimulite honeycomb cushion.

The cushion used in this study is made from an elastomers material TPU (Thermoplastic Polyurethane), non-toxic and safe for the people health and the environment, this material has good thermo-mechanical behavior, high compressive resistant, and puncture, tear and abrasion [14-15]. The flexible cellular TPU matrix is composed of preformed films in front of and heat-sealed in back side (Figure 2a). The alveolar films contain holes with diameter of 1.3 mm. Finally, the obtained matrix has
two thicknesses, 0.2 mm and 0.4 mm on the non-heat sealed plans and the assembly planes, respectively (Figure 2b). The distance between two parallel faces is in the order of 7 mm.

Figure 2. Thermal welding of the honeycomb cushion.

The CAD geometry of the half-honeycomb cushion was constructed by assembling 3 layers independent planes separated by SOLIDWORKS® software (Figure 2.c). The finite element modeling is created by commercial ABAQUS® software to investigate the effects of related pressure that appears at the contact interface buttocks/cushion. The honeycomb cushion, which was produced by Supraco® Company, made of thermoplastic polyurethane elastomer (TPU) with rate-independent hysteresis and viscoelastic behaviors. For isotropic hyperelastic materials (incompressibility material), the hyperelastic behaviors of the Mooney-Rivlin model are described by the strain energy potential function Eq. (1), \( W \) in the following form:

\[
W = C_{10}(\tilde{I}_1^{-3}) + C_{01}(\tilde{I}_2^{-3}) + \frac{2}{D_1}(J - 1)^2
\]  

(1)

Where \( \tilde{I}_1, \tilde{I}_2 \) are the first and the second invariant of the tensor, respectively, \( J \) is the Jacobine deformation. In Eq. (2) \( C_{10}, C_{01} \) and \( D_1 \) are the material-dependent parameters. \( D_1 = \frac{1-2\nu}{C_{10}+C_{01}} \), where \( \nu \) is the Poisson’s ratio of the material. The material parameters of the honeycomb cushion (TPU) were obtained from tensile and compressive tests that were conducted on the INSTRON 33R4204 machine. The viscoelastic properties of the honeycomb cushion (TPU) are determined by plotting the normalized stress with initial stress \( \sigma_0 \) against the time. The viscoelastic model has been obtained from relaxation tests by fitting a three-term Prony series (Eq. 2) to the relaxation data as follows:

\[
E(t) = 6.5(1 + 0.023e^{-t/12} + 0.08e^{-t/98} + 0.034e^{-t/1600})
\]  

(2)

The viscoelastic material parameters of the honeycomb cushion TPU were defined such that: \( N = 3; g_1 = 0.02 \) and \( \tau_1 = 12 \) s; \( g_2 = 0.074 \) and \( \tau_1 = 98 \) s, and \( g_3 = 0.031 \) and \( \tau_3 = 1600 \) s.

2.2. Experimental Set-up

We performed an experimental of compression with a honeycomb layer (8 cells) (Figure 3.a) to validate the comportment of the TPU material on the machine compression INSTRON 33R4204 (Figure 3.b). The experimental compression tests were carried out with a speed of 0.1 mm/s and a maximum displacement imposed of 3 mm.
Figure 3. Experimental test of a honeycomb layer on the machine compression ISTRON 33R4204 and non-linear stress–strain curve of honeycomb cushion material (TPU).

Figure 3.c represents the tensile curve obtained from the tests for the TPU material. From this figure, some material parameters are extracted and used for the model according to Kanyanta et al., [16]. The hyperelastic parameters Mooney-Rivlin of the honeycomb cushion TPU as flow: $C_{10} = 1.24$ Mpa; $C_{01} = 0.01$ Mpa; $D_1 = 2$ (Mpa$^{-1}$). In this study, all numerical simulations were performed with the parameters of the hyper-elastic Money-Rivlin behavior of the TPU material (honeycomb cushion).

An experimental device was designed and fabricated in order to compress a TPU honeycomb cushion with a human buttocks prototype created from the 3D model meets the requirements of the ISO 16840-2 standard [17] (Figure 4.a). This standard is set to the physical and mechanical characteristics of the seat cushion in order to measure the displacement that generated by a vertical load applied on the planar surface of the honeycomb cushion, at a distance of 127 mm from the rear edge of the buttocks (Figure 4.a). The compression tests were performed on the "Stimulite Cushion Classic", with an electromechanical pressure Instron 33R4204 (50 KN load cell) (Figure 4.b). A displacement is imposed on the cushion so that the maximum achieved load of 830 N and maintained through the use of a PID (Proportional Integral Derivative) controller (Figure 4.b).

Figure 4. Design and implementation of prototype experimental model rigid buttocks, temporal compression tests on Stimulite honeycomb cushion.

The compression tests with electromechanical pressure the Stimulite cushion were identified temporal force curve related to the mechanical behaviors of the cushion. To achieve the maximum load of 830 N, a displacement of 41.14 mm was applied on the buttock at the load set point to 127 mm.

2.3. Numerical simulation of contact problems

To compare experimental and numerical results and validate the comportment of the honeycomb cushion (TPU material). We proposed numerical model, a honeycomb layer of cushion model, with about 8 cells on each side and a height of $h = 20$ mm (Figure 5.a), the explicit dynamic approach (DE) (ABAQUS® software) was used to simulate our problematic.
Taking into account the interaction between the honeycomb layer with the two rigid plates was complicated. Indeed, we use to simulate the contact between the rigid plate and the honeycomb layer contact of a "surface-to-surface" type it possible to have numerical results much closer to the experimental curve (Figure 5.b) as well as a coherent deformation of the cells. The calculation time was 30 minutes with PC 16 processors of 32 Gb RAM. This approach allows the deformable elements in contact with the two rigid plates to undergo large deformations without "crossing" the rigid elements. Then we wanted to study the influence of the coulomb friction coefficient between these plates and the cells. Comparing the numerical curves obtained for three different coefficients of friction ($f = 0.5, 0.8$ and $0.95$) shows that the higher the coefficient of friction, the closer the numerical and experimental curves are (Figure 5.b), the contact so is almost sticky.

3. Numerical simulation applied to the honeycomb cushion

To reduce the calculation time and due to symmetries existing in the structure, only a half of rigid-buttock/honeycomb cushion model needs to be meshed and calculated. In this configuration, the model contains about that create a large mesh with a huge number of elements (Table 1).

| Mesh data | Type of elements | Type of elements | Type of elements | Type of elements |
|-----------|------------------|------------------|------------------|------------------|
| Honeycomb cushion | S3R | 8876760 | 4788759 |
| Rigid half-buttock | R3D3 | 42532 | 21268 |
| Rigid plate | R3D3 | 80 | 55 |
| Total | 8919372 | 4810082 |

The nodes of the mesh (Figure 6.b) located at the bottom surface (plane $Y = 0$) are encased (translations and zero rotations). To apply in the symmetry of the model, the nodes located in the symmetry plane (plane $X = 0$) are blocked in the X-direction translation and Y and Z-directions rotation. The honeycomb cushion used in this numerical simulation was only a half honeycomb cushion of 72 mm height. In addition, a half rigid-buttock, supposed in dimensionally stable, is requested with the application of a reduced dead weight of 41.5 kg applied in the vertical direction (Y).
Figure 6. a) The geometry human body/cushion and mesh of a half-buttock/cushion model; b) The force - displacement curve obtained from the experimental tests and numerical simulation for the honeycommb cushion.

In this configuration the calculation lasts approximately 48 hours 10 minutes with a PC 16 processors of 32 Gb of RAM. The vertical deformation (Y axis) of the cushion is shown in Figure 7.a. One can look at the maximum value of displacement on the honeycomb cushion in the vertical axis (Uy) of 41,33mm. The force – displacement curve compared with the experimental result above (compression tests on the traction machine (Figure 6.b)).

Figure 7. a) Vertical displacement (Y) (mm); b) Pressure distribution on seat cushion (MPa).

It can be observed that the contact pressure at the interface half-buttock/ honeycomb cushion varies between a maximum value of 642.1 kPa and on the cushion and 37.73 kPa on the rigid-buttock. In the next study, we will use of an innovative pressure pad for the evaluation the pressure distribution on the rigid buttock to compare with numerical simulation results.

4. Discussion
The numerical simulation of the structure, consists of a rigid buttock and a honeycomb cushion, is complicated and long computationally-intensive because it includes thousands of perforated cells that require very fine mesh. The structural decomposition of Stimulite cushion honeycomb allowed initially for focusing on the model with the isolated case of a cell to better understand their behaviors and to extend with many cases of alveolar parallelepiped volumes with approximately thousands of alveoli. The inspection of internal mechanical phenomena, such as stress and strain, revealed that it was possible to vary the operating parameters like the wall section, horizontal sheets addition, the position and diameter of the holes to make it less rigid the seat structure. The comfort depends upon the rigidity of the material, which ensures the strength and stability of the cushion. Hence, the finite element simulations can contribute to optimize the seating comfort by acting on this rigidity.

The proposed model in this paper is to model a cellular layer and it must be extended to multiple layers with different rigidity and mechanical properties depend on the type of TPU. The completed model will then study to obtain the impact of several geometrical parameters (diameter of the holes, sections, dimensions,...) on the mechanical behavior of the TPU cushion. Moreover, the optimal
solution will provide a cushion to the homogenized properties thereby decreasing the calculation time and will reduce manufacturing costs: optimized production, optimal ventilation, easy cleaning, cost … The study of microclimate intrinsic factor (thermo-mechanical behavior) by numerical simulation is also possible. Thermodynamics is a study to be taken into account in the development of this project over the perforated foam composition of the cushion. It has to be simulated, and checked, after seating, if the interface temperature is similar to the experimental results. Thermodynamics must also take advantage of the cushion. In addition, the model should be adapted in order to simulate the air flow through the layers of the cushion, whether the breakdown of Stimulite cushion is sufficient to avoid maceration effects. Most car seats are made of polyurethane foam. Industrial automotive, aerospace, furniture should be focused on these cellular TPU solutions that seem most appropriate to the fluidic effects.

5. Conclusion
The majority of studies deal with mainly pressure distribution, but study of the mechanical behavior of cushions is considered to prevent bedsores. It is possible to stand out from this research that primarily focused on the pressure. Other phenomena are considered. The thermo-fluid-mechanical coupling at the numerical simulation, which should innovate by using a reverse lookup. The idea may be, then, performed this test with a model diaper non-rigid biomechanics using a law close to human reality behavior. This first study, the mechanical behavior of honeycomb cushion helps to highlight the importance of using an effective method to improve the design of cushions to serve as an aid in preventing pressure ulcers: it is the numerical simulation using the finite element method.

6. References
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