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The Analytical Study of Garment Pressure on the Human Body Using Finite Elements

Abstract
This paper reports an analytical study of the contact pressure between an elastic garment and some parts of the human body whose geometries are cylindrical and conical, which is based on contact mechanics. The results of this model are compared with a numerical simulation using the finite element method as well as an experimental approach. This model is based on an analysis of contact areas between body and the garment. The numerical solution is done using ANSYS-9 software. The results showed good agreement between the analytical and software analysis. As a result, validation of the software is guaranteed for analysis of other areas of the body using this software. The results show a maximum error of about 7 percent between the theoretical and software solutions. An experimental case study shows there is always good agreement in the presence of friction which, was not included in the analytical and software solutions.

Key words: *contact mechanics, garment pressure, finite element.*

Introduction

Nowadays, there has been an increase in public demand for the desired garment. The choice of garment can be made on basis of the beauty, comfort or remedy features. Modern consumers demand apparel products with superior multifunctional and comfort performance to satisfy their physiological and psychical needs. The fit and size of the item of clothing are the most important factors, playing a vital role with respect to the pressure of the garment on the body. Contact mechanics is the fundamental theory for modelling garment pressure, since pressure arises from the contact between the body and a garment. By analysing the characteristics between the body and a garment, we developed a mechanical model based on the theory of contact mechanics.

Most of the researches on garment pressure that have been published have focused on conducting weave trials to measure this pressure and relevant subjective sensations [1 - 3]. Makabe et al [3] measured the garment pressure in the area around the waist. The results indicated that the pressure is negligible when it is in the range of 0 - 15 cN/cm^2. When the pressure is within the range of 15 - 25 cN/cm^2, there would only be slight discomfort, but extreme discomfort is perceived when the pressure exceeds 25 cN/cm^2.

In this paper, we present an analytical model of the human body and a garment to derive exact solutions for garment pressure, as well as validation analysis of software results, which has not been considered in previous researches. The computational model can simulate and predict the mechanical behaviour of garments without actually producing one. The level of garment pressure varies significantly for different knitted fabrics depending on four factors of the design fit of the garment, the thickness of the fabric, ther shape of the body part and the mechanical properties of parts of the human body as well as fabrics. An experimental study is also done for comparison.

Model assumptions

The model is based on the following series of assumptions as:

i) The human body is assumed to be a linear material whose behaviour is governed by Hook's law
ii) The garment is approximated as an isotropic and homogenous material
iii) The stress in the fabric thickness is assumed to be zero
iv) The friction between the body and the garment is neglected/negligible
v) The body is assumed to be a combination of a cylinder and cones,
vi) The contact between the body and garment is the same in all places.

Some of the assumptions, for instance the second one, are not true. As textile materials are not isotropic, we decided to make the model simple. In fact, we considered the garment as an elastic shell with linear material and non-linear geometry properties. The fabric used in this research work was hosiery, which is classified as a knitted fabric.

Governing equations

In ***Figure 1,*** a general shell of revolution, which is generated from revolving a flat curve around an axis on a surface, is considered. To make easy calculations, the positions of each point are specified with coordinates Θ, Φ, and r_o. The area of element ABCD is defined by two meridians and two parallel circles. The curve radiuses r_1 and r_2 at each point show the curve of meridian surface and the parallel plates, respectively. The relationship between radiuses r_o and r_2 is as follows:

$$r_o = r_2 \sin \phi \qquad (1)$$

Figures 2.a and ***2.b*** show two different views of element ABCD, cut from the shell shown in Figure 1. When the shell is subjected to an inner pressure, which is perpendicular to the curve surface, the meridian stress (σ_ϕ) and circumferential stress (σ_θ) are generated in the element.

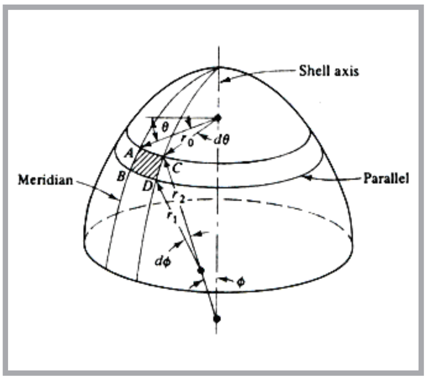

Figure 1. *A special shell used for the modelling and simulation of a body part, specified with pole coordinates.*

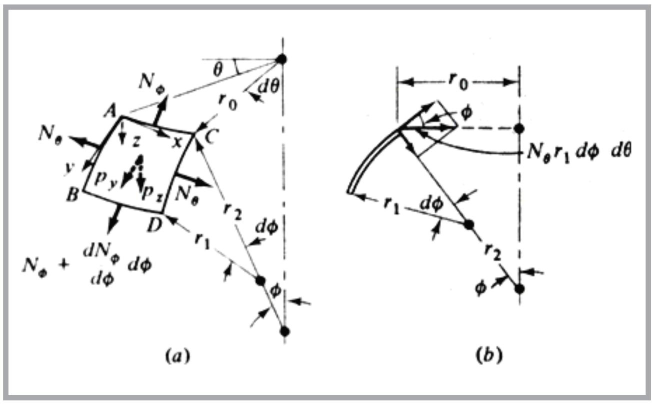

Figure 2. *Two side view of element ABCD.*

The area on which the pressure acts is equal to $(r_0 \cdot d\theta) \times (r_1 \cdot d\phi)$when we write the equilibrium equation of this element, which is perpendicular to the shell, the following equation is obtained:

$$\sigma_\theta \cdot h \cdot r_1 \cdot d\theta \cdot d\phi + \sigma_\phi \cdot h \cdot r_0 \cdot d\theta \cdot d\phi + \\ - p \cdot r_0 \cdot d\theta \cdot r_1 \cdot d\phi = 0 \qquad (2)$$

If we substitute $r_0 = r_2 \sin \phi$ in Equation (2), the following equation is obtained:

$$\sigma_\phi / r_1 + \sigma_\theta / r_2 = p/h \qquad (3)$$

Where h is the thickness of the shell. This basic equation is valid for all rotating shells whose deformation is symmetrical about the symmetric axis [4].

Cylindrical shell

To calculate the pressure generated in a rotating cylindrical shell, it is clear that $\varphi = \pi/2$ and $r_1 = \infty$, thus $r_2 = r_0$ and

$$\sigma_\theta / r_0 = p/h \qquad (4)$$

In this case, if the rotating cylindrical shell of radius r is placed on a rigid cylinder of radius $r_0 (r_0 > r)$, the shell will be extended in a circumferential direction. Its strain can be calculated from the following equation:

$$\varepsilon_\theta = (2\pi r_0 - 2\pi r)/2\pi r = r_0/r - 1 \qquad (5)$$

Also we know

$$\sigma_\theta = E \, \varepsilon_\theta \qquad (6)$$

From equations (4), (5) and (6) we can write:

$$p = E \cdot h \cdot (r_0/r - 1)//r_0 \qquad (7)$$

The above equation reveals the dependency of the contact pressure on such variables as the elastic modulus of the garment and its thickness.

Conical shell

In this case $r_1 = \infty$, $r_0 = r_2 \cos \alpha$. We may write similar equations to calculate the pressure on a cone resulting from a conical shell:

$$p = E \cdot h \cdot \cos \alpha \cdot (r_0/r - 1)/r_0 \qquad (8)$$

Where α is the angle of the cone, p is the pressure between the body and the cloth, E is the elasticity modulus of the fabric, r is the cloth radius and r_0 is the radius of the body where the pressure is calculated.

The finite element steps

To solve a contact equation using the finite element method in ANSYS-9 software, the following steps should be taken:

1. Using a suitable element (a shell element for the garment and a solid one for the body).
2. Dividing the object into some subdivisions (this step helps us to develop course or fine mesh in the object and results in less memory and time for computing).
3. Meshing each of the subdivision with suitable elements, which are selected in step 1.
4. Combining the equations, applying boundary conditions and loads, as well as trying to solve the system of simultaneous equations using conventional methods.
5. Obtaining unknown parameters by solving the equations.

Specifications of the body and garment

In this research work, the body was considered as a solid elastic material. The specifications of the body and knitted fabric are given in ***Table 1***. The specifications of the fabric were determined by a Instron tensile tester. The radius of the cylindrical fabric before it was worn on the cylindrical body was 0.025 m. Also, the assumed geometrical dimensions of the body and fabric in the conical case are presented in ***Table 2***.

Experimental study

To measure the pressure of the garment on the body, we applied lady hosiery of 18 cm diameter and 0.0004 m thickness, with a Young module of 24.5×10^3 Pa and a Poisson's ratio of 0.4. Some lines of 3 cm were marked on the hosiery. The foot and knee of the lady wearing the hosiery was as follows:

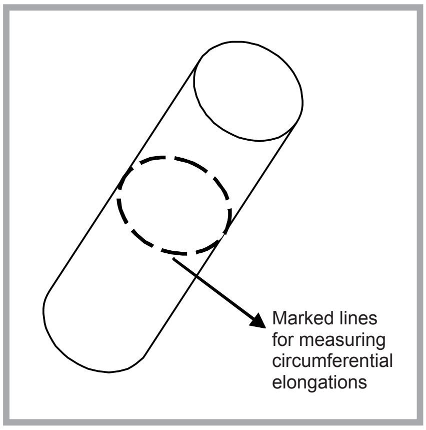

Figure 3. *The model for experimental study.*

- Circumference of the lower part of the leg: 18 cm
- Circumference of the top part of the leg: 23 cm
- Length of hosiery: 12 cm

Then the hosiery was put on a lady with a circular leg, as seen in ***Figure 3***. The

Table 1. *Specifications of the cylindrical body and fabric.*

	E, Pa	Poisson's ratio (n)	Thickness, mm	Length, mm	Radius, mm
Body	0.6×10^9	0.1	-	0.3	0.03
Fabric	0.23×10^3	0.4	0.85	0.3	variable

Table 2. *Specifications of the conical body and fabric.*

	Small radius(m)	Large radius (m)	Thickness (mm)	Length (m)
Body	0.03	0.04	-	0.3
Fabric	variable	variable	0.85	0.3

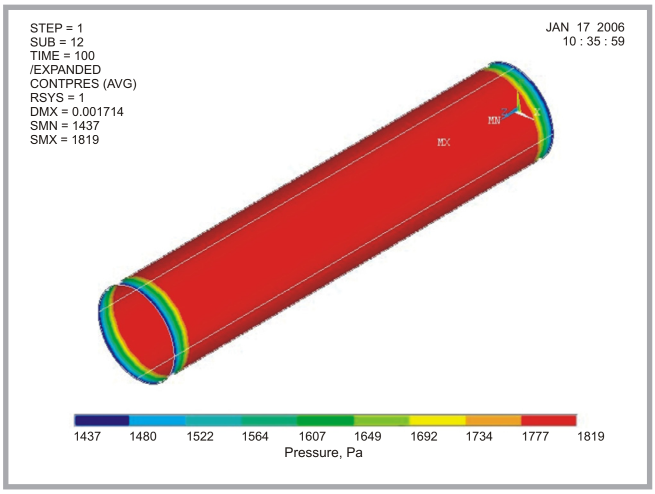

Figure 4. *Distribution of pressure between the body and cloth.*

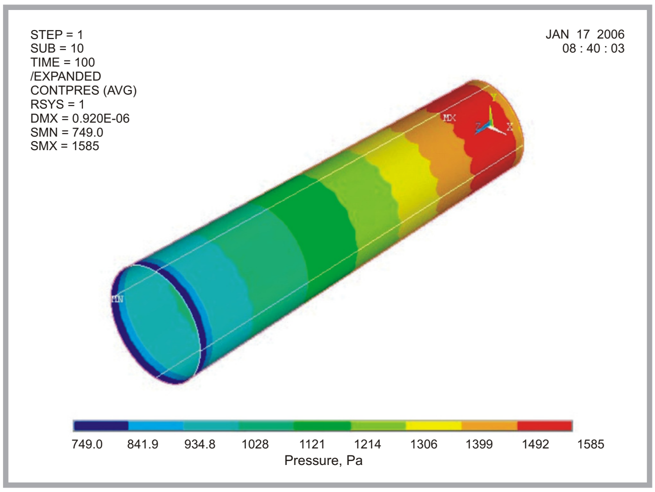

Figure 5. *The pressure created in a cloth worn on the cone.*

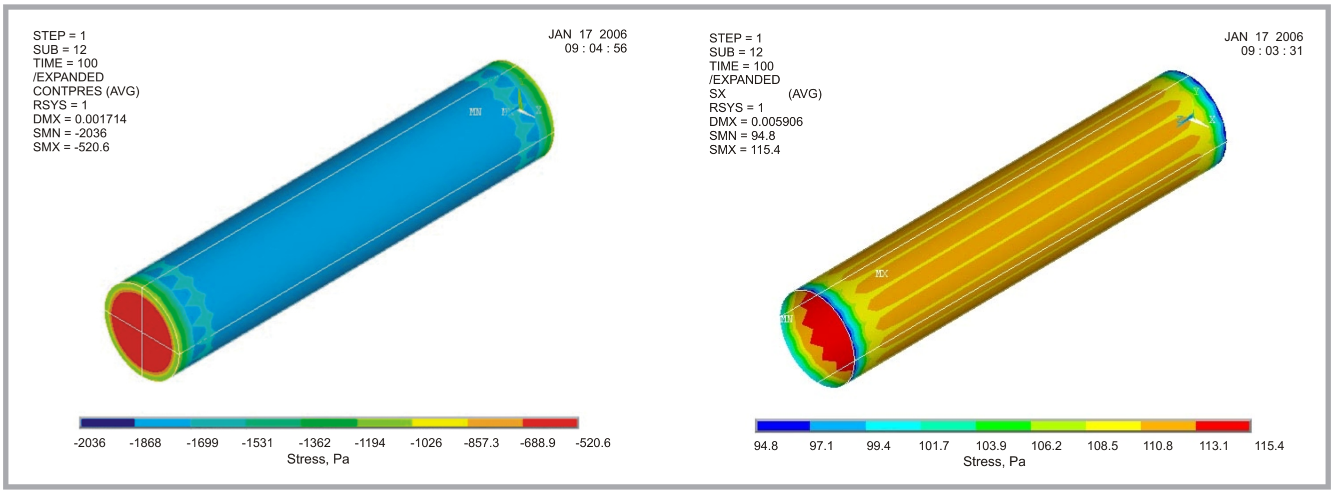

Figure 6. *Distribution of stress on the body and cloth.*

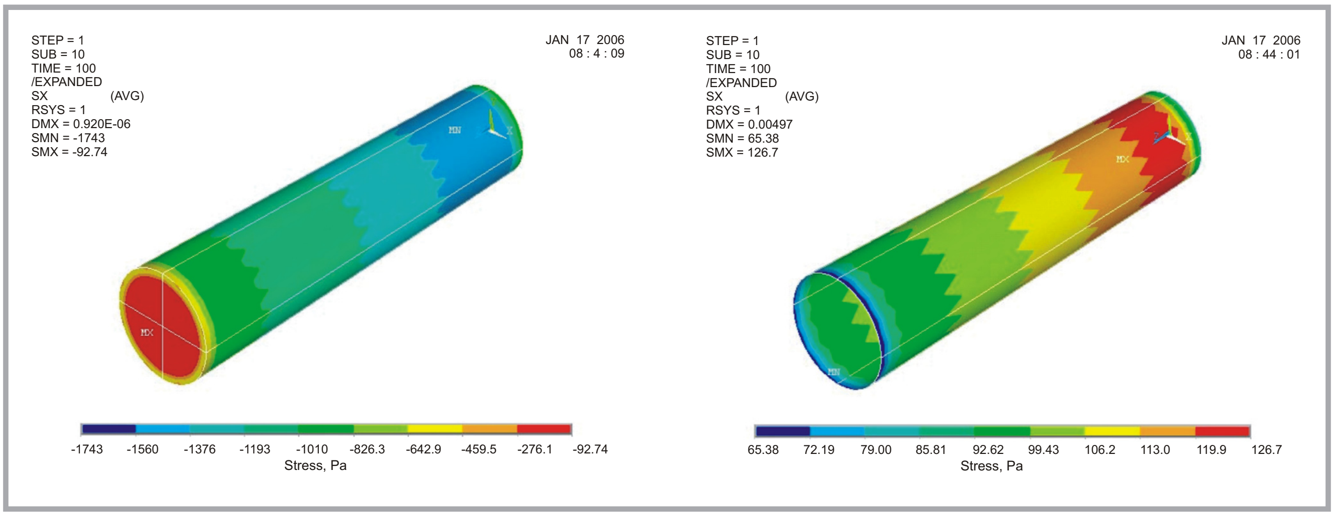

Figure 7. *Distribution of stress in the cone.*

lines marked on the hosiery changed from 4 - 10 cm. The circumferential strain (ε_θ) of each part was calculated by dividing the elongation of the relevant line by its initial length.

Results and discussion

Figure 4 illustrates the distribution of the pressure between the cloth and the body. The units are in Pa, which can be converted into cN/cm^2 by multiplying it by 10^{-2}. As is observed from this figure, the maximum pressure is about 15 cN/cm^2, which is in agreement with previous research works and would be quite acceptable.

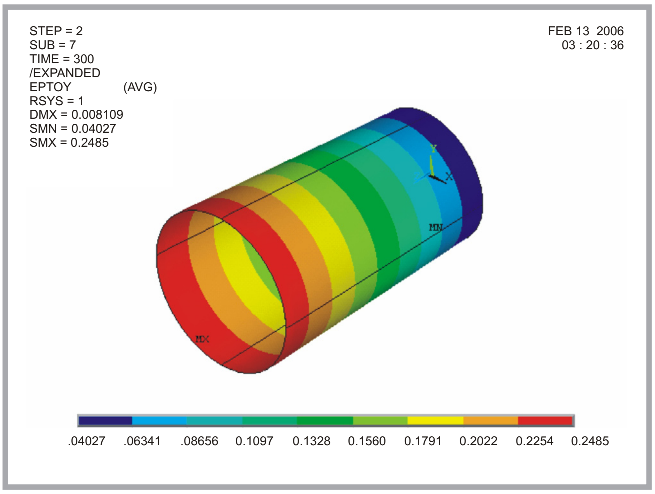

Figure 8. *The circumferential strain.*

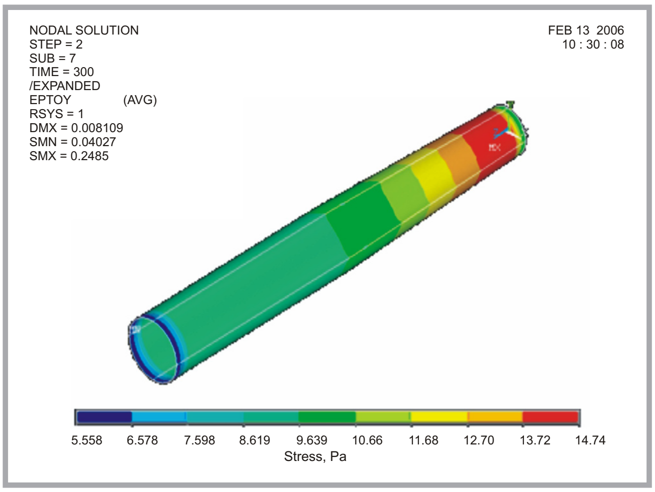

Figure 9. *Distribution of stress of the cloth on a hand.*

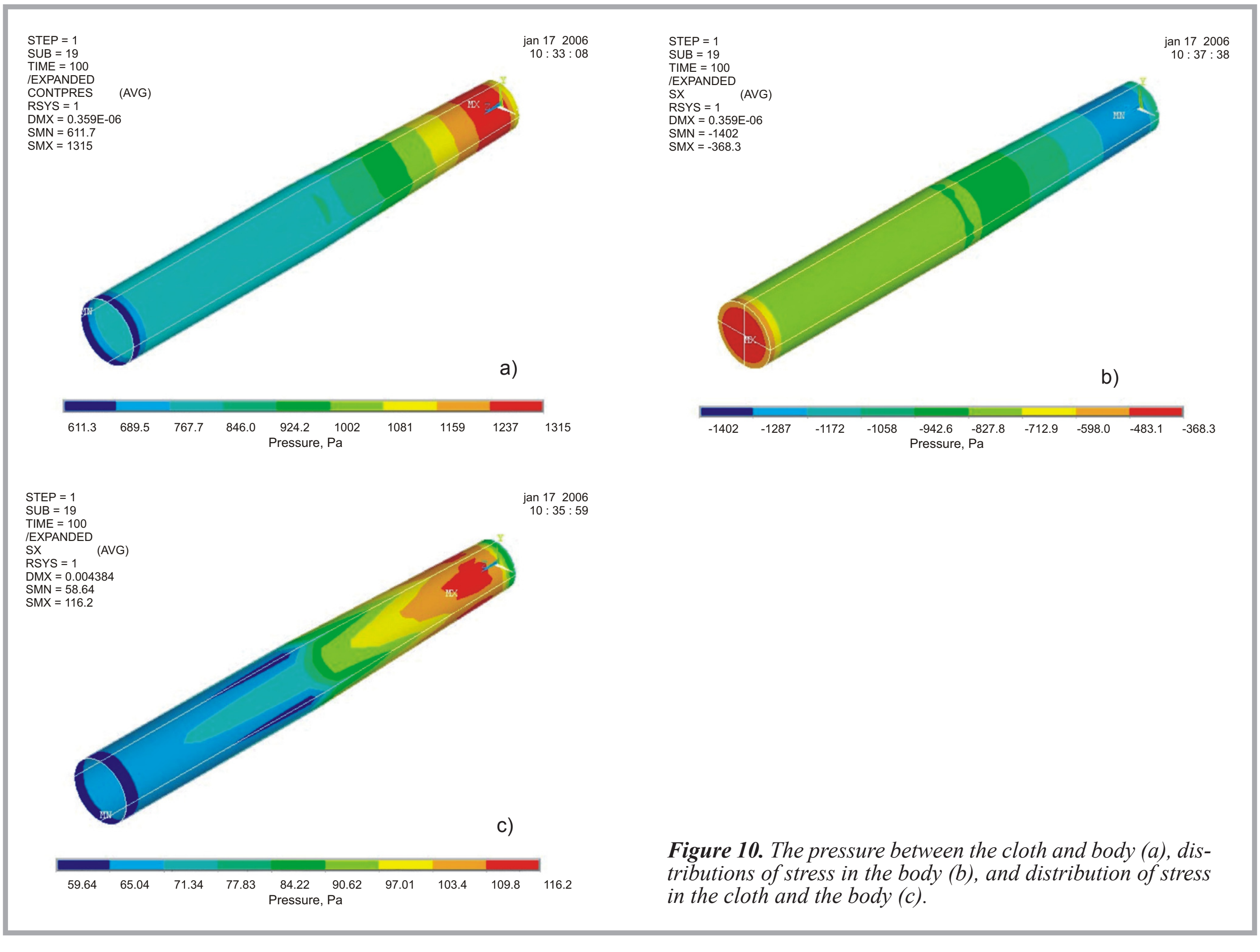

Figure 10. *The pressure between the cloth and body (a), distributions of stress in the body (b), and distribution of stress in the cloth and the body (c).*

Figure 5 indicates the pressure created in a cone. In this model the cloth worn on the cone was sewn as a cone, so that its circumferential strain in the length of the cone is constant. Therefore, it is acceptable that the pressure on cones of lower diameter, is higher. It is clearly obvious that when the diameter and dimensions of the fabric decrease, it will tolerate higher stress.

Figure 6 shows the distribution of the stress on the body and cloth. Negative values of stress in the body shows the pressure on it, whereas positive values of stress in the cloth shows its elongation.

Figure 7 indicates the distribution of stress in the cone. The stress created on the body's dimensions is about 10 - 20 cN/cm^2, which is a reasonable and acceptable pressure according to results obtained from previous research works.

Figure 8 shows the circumferential strain (ε_θ) of the hosiery, calculated and plotted by ANSYS software. The results obtained from the measurement indicate fairly good agreement between the results obtained from the simulation, (***Figure 8***),

***Table 3.** Theoretical and ANSYS contact pressures solutions for cylindrical case.*

Radius of body, m	0.0245	0.025	0.0255	0.026	0.027
Theory, Pa	1463	1303	1150	1003	724
ANSYS, Pa	1395	1282	1144	1008	757
Error, %	4.8	1.7	1.5	1.6	4.5

***Table 4.** Theoretical and ANSYS contact pressures solutions for various r in conical case.*

Radius of body, m	0.03	0.0325	0.035	0.0375	0.04
Radius of fabric, m	0.025	0.0275	0.03	0.0325	0.035
Theory, Pa	1303	1094	931	803	699
ANSYS, Pa	1216	1073	920	789	646
Error, %	6.6	2	1.1	1.6	7.05

and the experiments. The maximum error is about 10 percent. The slight difference between the results may be due to ignoring the friction coefficient in the model used for simulation.

At this stage the combination of cylinder and cone as well as ellipse was studied. As mentioned earlier, there is good agreement between the results of theory and experiments for cylindrical and conical shapes; we can claim that this method can be applied for other geometrical shapes. ***Figure 9*** illustrates the distribution of stress on a body based in part on hand dimensions.

Finally, ***Tables 3*** and ***4*** compare the analytical and software results for cylinder and cone cases.

Since the strains are measured at the experimental stage, it is preferred to compare the theoretical strains calculated by the ANSYS program were those obtained experimentally. As a result, we get ***Table 5,*** which shows good agreement between them. It is noted that the friction was not considered in the theoretical ANSYS calculation, although it influenced the experimental results at the experimental stage.

We combine cylinder and cone as some parts of the body are similar to them. With this combination parts of the body can be modelled and simulated. Consequently, the body can be adorned in cloth of arbitrary diameter, and the pressure and the stress from the cloth on the body can be predicted with high accuracy before sewing the cloth. This simulation can be used for elastic bands, medical supports, etc. so that the user feels maximum comfort. ***Figure 10*** shows the pressure between the cloth and the body in this model, as well as the distribution of stress in the cloth and body, respectively.

***Table 5.** ANSYS and experimental values of strains expressed as a ratio.*

Method	**Minimum strain**	**Maximum strain**
ANSYS	0.0403	0.248
Experimental	0.036	0.23
Error, %	10	7

Conclusions

A comparative study of analytical software and experimental methods for computation of the contact pressure between the body and garment was presented. This study shows good agreement between theory and software as well as experimental solutions. Therefore, ANSYS software can compute contact pressures with enough accuracy in different cases of geometrical complexity. The results showed that there is a maximum error of about 7 percent between these two methods. This research also confirmed the validity of the results obtained from the commercial software used. The limitation of this research is the rigid body assumption.

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