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Research paper

Quantifying and Comparing the Hyperelastic Properties of Skin, Leather and Silicone

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Abstract

Skin is the largest and an important organ of an animal or human body. Skin provides multiple important functions and it exhibits complex behaviour. The injuries due to burn, damage and accident have led to research in understanding skin behaviour as this knowledge could lead to producing good quality of synthetic skin. To date, the properties of skin are still not well quantified. Therefore, this study aims to quantify and compare the hyperelastic properties of skin, leather and silicone using three common hyperelastic constitutive models which are Neo-Hookean, Mooney-Rivlin and Ogden model. The specimens were prepared using specimens template according to ASTM D2209 testing standard and tested under uniaxial tension with speed rate of 254 mm/min. The numerical analysis was performed to quantify and determine the hyperelastic material constants using the selected hyperelastic constitutive models. The material constants were determined using Excel (solver) and curve fitting technique was used to match the stress-stretch curve to experimental data. The results show that the Mooney-Rivlin model produces the best fit curve for all three specimens. Hence, it can be concluded that all the three hyperelastic models, especially Mooney-Rivlin are capable to determine the mechanical behaviour of skin, leather and silicone rubber.

Keywords: *Skin, leather, silicone, , hyperelastic, tensile test*

1. Introduction

Skin is the largest organ of an animal or human body and plays multiple important functions; such as thermal regulation, fluid balance and protecting the body from infections [1]. Skin exhibits complex behaviour due to its complex structure [2]. The injuries due to burn, damage and accident have led to important research in understanding the behaviour of skin in order to develop a good quality of synthetic skin or skin substitute [3]. The introduction of skin substitute was first introduced by Riverdin in 1871 [4]. Then, the skin development continued in attempt to find the ideal characteristic of skin substitute and this led to many more investigation to understand skin complex structure [4, 5]. The limited number of skin donor has also been crucial that leads to determining the ideal skin substitute. Apart from that, the shortage of natural skin graft has also led to the development of skin substitute in order to heal and cure wound due to injuries, burns or dermal disorders [6]. Relatively, various temporary or permanent skin substitutes are demanded to recover the wound.

In terms of mechanical characteristics, skin behaves in a complex manner, which skin is known to be highly non-linear, inhomogeneous and viscoelastic material [7, 8]. Shergold et. Al [8] carried-out experiment to compare the mechanical behaviour of pig skin and silicone at low and high strain rates in which to determine the mechanical response of those two materials respectively. The pig skin was chosen due to similar mechanical characteristic to human skin in which in order to determine the strain rate sensitivity of the materials. Apart from that, the study of skin mechanical properties not only important for skin substitutes, it is also widely usable in other applications such as forensic science and impact biomechanics [9,10,11]. The tensile experiment has been conducted by Gallagher et. al [2] in order to determine the effect of dynamic speed on mechanical properties of skin. They used human cadaver as their specimen with specific location and orientation as respect to Langer's lines. Lim et. Al [12] states that, the mechanical behaviour of skin is important for reconstruction procedures of in order to predict the skin damage by vehicle crashes or punching accidents. Hence, the study of mechanical properties on pig skin was carried out using uniaxial tensile test to investigate the stress-strain response at quasi-static and dynamic rates. The investigation using hyperelastic material model also will be useful in determining the mechanical behaviour of skin which are originally developed for rubber materials such as Neo-Hookean, Mooney-Rivlin and Ogden models; are commonly adapted for soft tissues [13, 14]. Chen et. al 2013 [15], used three material model which were Neo-Hookean, Mooney-Rivlin and Yeoh to study the hyperelastic constitutive parameters from load-depth curves obtain from indentation test of silicone rubber. Neo-Hookean material model has been used by Karimi et. al [16] to determine the anisotropic nonlinear mechanical properties of rat and mice skin tissue using the role of fiber fiber orientations into that constitutive equation. In that study, experiment and numerical analysis has been conducted and in results of good agreement between both analysis according to stress-strain relationship behaviour.

Based on these literatures, it can be concluded that to date, the properties of skin are still not well quantified and established. Therefore, this paper aims to quantify and compare the hyperelastic properties of bovine, leather (goat) and normal grade silicone under uniaxial tension based on the three most common hyperelastic constitutive equations, which are Neo-Hookean, Mooney-Rivlin and Ogden models. This study is novel as till now there is no similar study, adopting the similar materials has been reported before.

2. Methodology

In general, the methodology involves specimen preparation, tensile test, and numerical analysis as described in the following sections.

2.1. Specimen Preparations

Initially, the work involved material selections and preparation of specimens. In this study, the selected materials were bovine skin, leather (goat) and silicone rubber. The specimens were prepared according to the ASTM international standard for leather, which is ASTM D2209 for uniaxial tensile test [17]. The specimen specification according to ASTM D2209 is shown in Fig. 1 with the dimension of 171 mm length and 31.8 mm width.

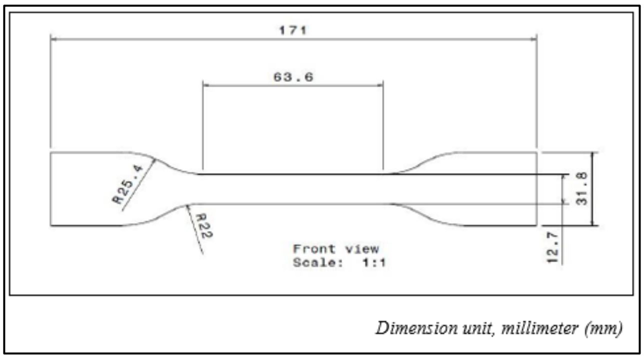

Fig. 1: Schematic Drawing of ASTM D2209 Standard for Leather

The specimens for skin were selected from a two years old male bovine, bought fresh from a slaughterhouse. The specimens for leather were processed by manufacturer and ready to be used as product. They were bought from Mega KSL Trading located at Seri Kembangan, Selangor. The leather (goat) specimens were prepared according to longitudinal direction of goat body. The specimens for the silicone were fabricated from the sheet of normal grade silicone rubber, with the dimension of 1 m x 1 m x 3mm thickness, supplied by Tatlee Engineering, Johor Baharu, Malaysia.

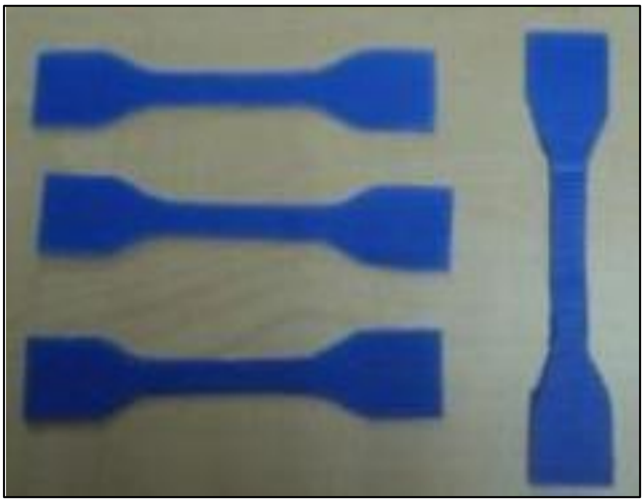

Fig. 2: Specimens template

To ease the fabrication of standard size of specimens, specimens template (Fig. 2) were prepared using blue plastic mould board. This was to ensure that, all specimens fulfill the exact requirement and specification of ASTM D2209. The schematic drawing of ASTM D2209 with scale 1:1 was printed and mapped on to blue plastic mould board. Then, all the specimens were cut accurately to the specimen template and ready (Fig. 3) for uniaxial tensile tests.

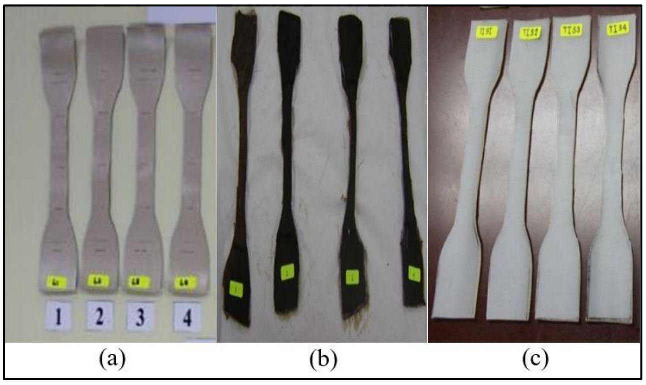

Fig. 3: Test specimens (a) Leather, (b) Bovine skin, (c) Silicone rubber

2.2. Tensile Test

The uniaxial tensile test was conducted at the Strength of Materials Laboratory, Faculty of Mechanical Engineering UiTM Shah Alam, Selangor. Tensile tests were carried out using Universal Testing Machine (Instron, Dynatup 3382). According to ASTM D2209 standard, the speed rate was set to 254 mm/min. In order to avoid specimen slippage during tensile test, sand paper were used for gripping.

From the tensile testing procedure, the original output of load-extension data were generated, where the units were in Newton (N) and millimetre (mm) respectively. These measured data were extracted into a spreadsheet (xls). From the load-extension data, normal strain, ε, and principal stretch, λ, were computed using Eq. 1 and Eq. 2.

$$\varepsilon = \Delta L / L \qquad \text{(Eq. 1)}$$

where ΔL is the extension (elongation in mm) and L is the original length of the specimens. From there, principal stretch, λ, was computed using Eq. 4.

$$\lambda = \varepsilon + 1 \qquad \text{(Eq. 2)}$$

2.3. Numerical Analysis

The numerical analysis was employed to quantify and determine the hyperelastic material constants of the tested specimens (bovine skin. leather and silicone rubber). The most common hyperelastic constitutive models were employed, which were Neo-Hookean, Mooney-Rivlin and Ogden constitutive equations.

Eq. 3 presents the general strain energy density functions, W of the Neo-Hookean model for an incompressible material [18].

$$W = C_1(I_1 - 3) \qquad \text{Eq. 3}$$

Where C_1 is a material constant and I_1 is the first invariant of the left Cauchy-Green deformation tensor's element. Considering neo-Hookean model, where the material is assumed to be isotropic, hyperelastic and incompressible, the relationship between engineering stress, σ_E, and principal stretch, λ, is represented by Eq. 4.

$$\sigma_E = 2C_1 (\lambda - 1/\lambda^2) \qquad \text{Eq. 4}$$

Eq. 5 presents the general strain energy density functions, W of the Mooney-Rivlin model [19,20], where C_1 and C_2 are material constants; and I_1 and I_2 are the first and second invariant of the left Cauchy-Green deformation tensor's element.

$$W = C_1(I_1 - 3) + C_2(I_2 - 3) \qquad \text{Eq. 5}$$

Considering Mooney-Rivlin model, where the material is assumed to be isotropic, hyperelastic and incompressible, the relationship between engineering stress, σ_E, and principal stretch, λ, is represented by Eq. 6.

$$\sigma_E = 1/\lambda\,(2C_1+2C_1/\lambda) + (\lambda^2+1/\lambda) \quad \text{Eq. 6}$$

Eq. 7 presents the general strain energy density functions, W of the Ogden model, where, λj (j =1,2,3) is the principal stretch ratio, and μi and αi are empirically determined material constants [21].

$$W = \sum_{i=1}^{n} \frac{\mu_i}{\alpha_i}(\lambda_1^{\alpha_i}+\lambda_2^{\alpha_i}+\lambda_3^{\alpha_i}-3) \quad \text{Eq. 7}$$

Considering Ogden model, where the material is assumed to be isotropic, hyperelastic and incompressible, the relation of engineering stress, σ_E and principal stretches, λ, is represented by Eq. 8.

$$\sigma_E = \mu/\lambda\,(\lambda^{\alpha} - \lambda^{-\alpha/2}) \quad \text{Eq. 8}$$

From the experimental data (load-deformation and stress-stretch), Excel solver was used to curve fit the stress-stretch curves. The best fit data to the curves constituted the material constants. This was performed for all three hyperelastic constitutive equations. Basic statistical analysis to compute mean, standard deviation and variance was also performed.
Based on Eq. 4, Eq. 6 and Eq. 8, (engineering stress, σ_E for the Neo-Hookean, Mooney-Rivlin and Ogden models respectively), a stress-stretch (σ_E versus λ) graph was plotted using a spreadsheet (Microsoft Excel) and the curves for each specimens were denoted as test (experiment) results. The mean of the stress-stretch value was then calculated and plotted. This curve (mean stress-stretch value) serves as the reference curve and used for the curve fitting procedure.

3. Results and Discussion

3.1. Tensile Test Results

In general, the results from the tensile tests produced data that were mathematically solved and quantified into material constants describing the hyperelastic properties of the specimens (bovine skin, leather (goat) and silicone rubber). Engineering stress, extension and strain data were obtained from the uniaxial tensile tests. The generated data and results of the basic statistical analysis for three different materials which are bovine skin, leather and silicone rubber are tabulated in Table 1, Table 2 and Table 3 respectively. As mentioned earlier, all the specimens were tested according to ASTM D2209 standard for leather. In general, Table 1. Table 2 and Table 3 show the computed values of mean, standard deviation and variance. The computed values of variance are relatively very small which are less than 1 % for bovine skin, silicone and leather materials.

Table 1: Tensile test results (Stress-Stretch data) for Bovine Skin

Stress (MPa)	Stretch						
	Specimen				Mean	Std. Dev	Var.
	1	2	3	4			
0.00	1.000	1.000	1.003	1.003	1.002	0.0018	0.0000
0.40	1.123	1.225	1.199	1.304	1.214	0.0735	0.0054
0.80	1.163	1.262	1.231	1.351	1.252	0.0783	0.0061
1.20	1.194	1.288	1.257	1.377	1.279	0.0764	0.0058
1.60	1.220	1.309	1.272	1.404	1.301	0.0774	0.0060
2.00	1.241	1.330	1.288	1.419	1.320	0.0757	0.0057
2.40	1.257	1.346	1.304	1.440	1.337	0.0780	0.0061

Table 2: Tensile test results (Stress-Stretch data) for Leather

Stress (MPa)	Stretch						
	Specimen				Mean	Std. Dev	Var.
	1	2	3	4			
0.00	1.000	1.000	1.0000	1.0000	1.000	0.0000	0.0000
1.00	1.020	1.021	1.0190	1.0240	1.021	0.0022	0.0000
2.00	1.038	1.045	1.0270	1.0470	1.042	0.0090	0.0001
3.00	1.048	1.038	1.0680	1.0780	1.058	0.0183	0.0003
4.00	1.101	1.061	1.0510	1.0710	1.071	0.0216	0.0005
5.00	1.120	1.072	1.0870	1.0490	1.082	0.0298	0.0009
6.00	1.170	1.090	1.0900	1.0670	1.093	0.0452	0.0020
7.00	1.22	1.082	1.072	1.112	1.102	0.0688	0.0047
8.00	1.001	1.110	1.200	1.129	1.110	0.0823	0.0068
9.00	1.008	1.130	1.230	1.104	1.118	0.0913	0.0083
10.00	1.024	1.121	1.250	1.105	1.125	0.0935	0.0087
11.00	1.235	1.001	1.101	1.191	1.132	0.1036	0.0107
12.00	1.305	1.039	1.145	1.067	1.139	0.1194	0.0143
13.00	1.431	1.100	1.245	1.145	1.145	0.1469	0.0216

Table 3: Tensile test results (Stress-Stretch data) for Silicone

Stress (MPa)	Stretch						
	Specimen				Mean	Std. Dev	Var.
	1	2	3	4			
0.00	1.001	1.000	1.000	1.000	0.800	0.000	1.43E-07
0.40	1.066	1.067	1.063	1.059	0.851	0.004	1.54E-05
0.80	1.178	1.188	1.165	1.184	0.943	0.010	1.02E-04
1.20	1.326	1.344	1.315	1.337	1.064	0.013	1.57E-04
1.60	1.479	1.494	1/468	1.501	1.189	0.015	2.17E-04
2.00	1.639	1.656	1.624	1.670	1.318	0.020	4.03E-04
2.40	1.789	1.821	1.771	1.833	1.443	0.028	8.06E-04

Therefore, the tensile test results are acceptable since the overall computed variance is less than 5%. This proves that the tensile tests have been conducted consistently and thus later, the numerical analyses performed are reliable.

3.2. Neo-Hookean Hyperelastic Material Constant

Table 4 shows the quantified Neo-Hookean material constant to describe the hyperelastic properties of leather, bovine skin and silicone rubber. Based on the reference curves (data from tensile tests), the value of the neo-Hookean material constants were determined for all the three materials from the curve fitting procedure. The Neo-Hookean material constants, C_1 were obtained from Microsoft Excel solver based on Neo-Hookean strain energy density function. The material constant, C_1 for bovine skin, leather and silicone rubber are found to be 1.0817, 0.781 and 14.209 respectively.

Table 4: Neo-Hookean material constants, C_1

Material	Material constant C_1
Bovine skin	1.0817
Leather	14.209
Silicone (Normal Grade)	0.781

Fig. 4 shows the stress-stretch (σ_E versus λ) curves of Neo-Hookean hyperelastic properties for bovine skin, leather and silicone rubber. The graphs for both experimental and numerical results are plotted. From Figure 4, the graph shows the curves fitted for all the three specimens based on the quantified material constants, C_1 (Table 4). Considering the same amount of uniaxial load (2 MPa) and in terms of deformation, the silicone rubber specimens show the highest stretch compared to bovine skin and leather. This result shows that, the stiffness of leather specimens is highest (C_1 = 14.21), followed by bovine skin (C_1 = 1.08) and silicone rubber (C_1 = 0.78). According to Figure 4, it can be seen that the results of numerical approach (stress-stretch (σ_E versus λ) curves) is close to the experimental results, with only a slight difference. This indicates that the numerical results obtained from the developed Microsoft Excel programme based Neo-Hookean strain energy density function is reliable and accurate enough in determining the mechanical properties of skin, leather and silicone rubber.

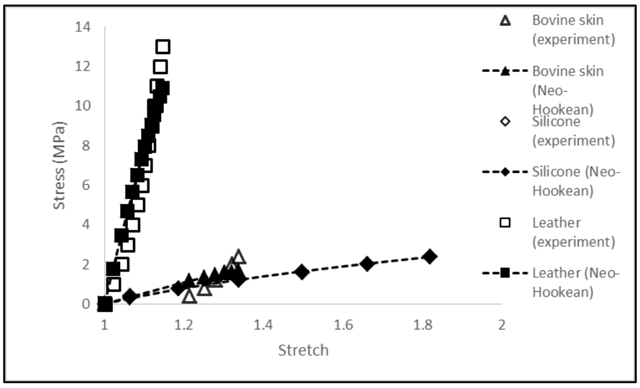

Fig. 4: Stress-stretch (σ_E versus λ) graph for Neo-Hookean model

3.2. Mooney-Rivlin Material Constants

Table 5 shows the quantified Mooney-Rivlin material constants to describe the hyperelastic properties of bovine skin, leather and silicone rubber. Based on the reference curves (data from tensile tests), the value of the Mooney-Rivlin material constants were determined for all the three materials from the curve fitting procedure. The Mooney-Rivlin material constants, C_1 and C_2 were obtained from Microsoft Excel solver based on Mooney-Rivlin strain energy density function. The material constant, C_1 and C_2 for bovine skin, leather and silicone rubber are found to be C_1=13.349 C_2=-15.851, C_1=112.864 C_2=110.125 and C_1=0.728 C_2=0.0863 respectively.

Table 5: Mooney-Rivlin material constants, C_1 and C_2

Material	Material constants	
	C_1	C_2
Bovine skin	13.349	-15.851
Leather	112.864	-110.125
Silicone (Normal Grade)	0.728	0.0863

Fig. 5 shows the stress-stretch (σ_E versus λ) curves of Mooney-Rivlin hyperelastic properties for bovine skin, leather and silicone rubber plotted from the quantified material constants, C_1 and C_2 (Table 5). The graphs for both experimental and numerical results are plotted. By observing Figure 5, it shows that the results between experimental and numerical approached are in good agreement. It is also found that the graphs quantified from the Mooney-Rivlin hyperelastic model is closer to the results quantified from the Neo-Hookean hyperelastic model (Figure 4).

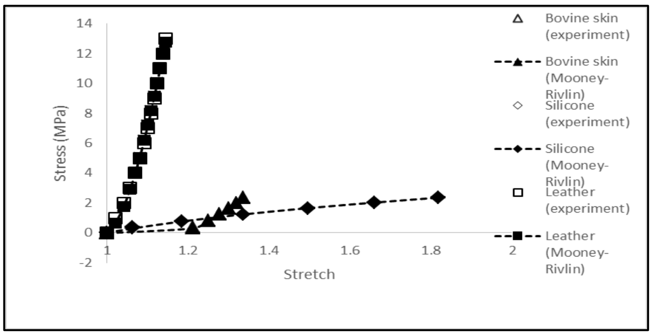

Fig. 5: Stress-stretch (σ_E versus λ) graph for Mooney-Rivlin model

3.3. Ogden Material Coefficient and Exponent

Table 6 shows the quantified Ogden material coefficient, μ and exponent, α to describe the hyperelastic properties of bovine skin, leather and silicone rubber. Based on the reference curves (data from tensile tests), the value of the Ogden material coefficient were determined for all the three materials from the curve fitting procedure. The Ogden material coefficient, μ and exponents, α were obtained from Microsoft Excel solver based Ogden strain energy density function. The material coefficients, μ and exponents, α for bovine skin, leather and silicone rubber are found to be μ=0.023 α=17.780, μ=1.647 α=1.928 and μ=11.827 α=15.885 respectively.

Table 6: Ogden material constant

Material	Material constants	
	μ	α
Bovine skin	0.023	17.780
Leather	1.827	15.885
Silicone Normal Grade	1.647	1.928

Fig. 6 shows the stress-stretch (σ_E versus λ) curves of Ogden hyperelastic properties for bovine skin, leather and silicone rubber. The graphs for both experimental and numerical results are plotted for material coefficient, μ and exponents, α in Table 6. From the curve fitting results in Fig. 6, the curve for leather and silicone between experimental and numerical are more accurate compared to bovine skin.

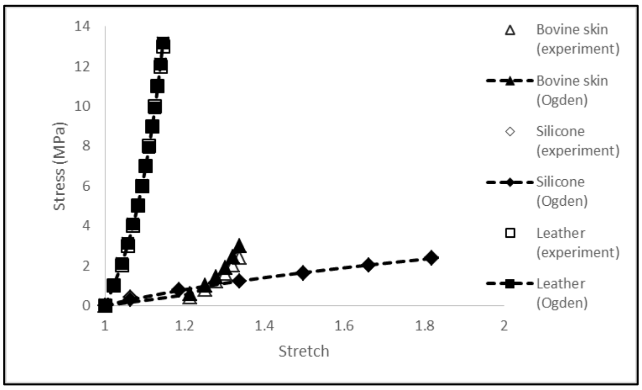

Fig. 6: Stress-stretch (σ_E versus λ) graph for Ogden model

Finally, for overall observation from all the results (Fig. 4 to Fig. 6) of uniaxial tensile tests and numerical analyses using three common hyperelastic material models, it is interesting to observe that the best curve fitting results for all the three materials (skin, leather and silicone rubber) are obtained when using the Mooney-Rivlin model. When comparing the tensile behaviour of bovine skin, leather and silicone rubber from all the stress-stretch (σ_E versus λ) curves (Fig. 4 to Fig. 6), it is also interesting to point out that leather is found to be the stiffest followed by bovine skin and silicone rubber.

4. Conclusion

This paper aims to quantify and compare the hyperelastic properties of bovine, leather (goat) and normal grade silicone under uniaxial tension based on the three most common hyperelastic constitutive equations, which are Neo-Hookean, Mooney-Rivlin and Ogden models. The data generated and results obtained prove that the main aim of the study has been achieved successfully. The main findings deduced from the results are (1) the best curve fit model for all the three materials (skin, leather and silicone rubber) is Mooney-Rivlin hyperelastic model. The Mooney-Rivlin material constant, C_1 and C_2 for bovine skin, leather and silicone rubber are found to be C_1=13.349 C_2=-15.851, C_1=112.864 C_2=110.125 and C_1=0.728 C_2=0.0863 respectively. This also shows that the most stiff material is leather, followed by bovine skin and silicone rubber. These results will contribute to enhance knowledge about determining the mechanical behaviour of skin, leather and silicone rubber using hyperelastic material models compared to experimental procedure. Therefore, it can be concluded that this study is significant. Further investigation related to the dynamic stress analysis of skin and synthetic skin is undergoing and the results will be reported in the near future.

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