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Tribological investigation of human skin friction with polytetrafluoroethylene PTFE under different boundary conditions

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Abstract. This paper is an experimental investigation on the interaction between the human finger and polytetrafluoroethylene (PTFE) with regards to friction. Three male Asian volunteers aged 24, 52 and 66 were asked to participate. The experimental setup consisted on a circle tipped probe being placed in contact with the ring finger of the volunteers and dragged over the surface of the finger with an applied load of (1-12) N. The friction phenomenon was evaluated in both dry and wet conditions using the CETR UMT-2 tribometer from the Department of Machine Elements and Tribology at University Politehnica of Bucharest. Contact adhesion was also studied, and it was found out that younger skin exhibits a greater adhesion component.

1. Introduction

Polymeric materials have become very commonly used in many aspects of daily human life due to their excellent overall physical, chemical, and mechanical properties including them being lightweight and safe to be manipulated in direct contact with human skin. Their versatility means that almost all conditions can be met with a certain type of polymeric materials. A short list comprising of various types of the polymers can be consulted below [1]:

- Polyethylene (Polythene PE), low and high densities
- Polyvinyl Chloride (PVC)
- Polyvinyl Acetate (PVA)
- Polymethyl Methacrylate (Perspex)
- Polytetrafluoroethylene (Teflon PTFE)

Teflon was chosen for the investigation as it is one of the most commonly used polymeric materials and that leads to an investigation on a direct tribological interaction between the human skin and it. The importance of this investigation is to facilitate lower limb amputees by improving the direct contact conditions between the skin of the stump and a polymeric prosthetic socket. This is a great issue especially in countries with high relative humidity levels and wide range of ambient temperatures during the year [2-4].

Teflon at a Glance: Polytetrafluoroethylene or Teflon is one of the most used polymer, and the polymeric chain mainly consists of a series of carbon and fluorine atoms.

This polymer lattice structure is composed of amorphous and crystalline zones. This structure can easily be observed under microscope. Teflon's physical and mechanical properties can be observed in tables 1 and 2 [5].

Table 1. Physical properties of a Teflon [5].

	Density $\left({}^{Kg}/_{m^3} \right)$	Viscosity (cP)*10^{14}	Melting Temperature $(°C)$	Maximum Service Temperature $(°C)$	Glass Transition Temp. T_g $(°C)$
Physical properties	2070	5.05	327	260	126

Table 2. Mechanical properties of a Teflon [5].

	Yield Strength (MPa)	Elongation %	Young Modulus (MPa)	Shear Strength (MPa)	Coefficient of Friction
Mechanical Properties	20.5	300	564	15.1	0.0630

Where cP: Centipoise, T_g: Glass Transition Temperature, Human skin at a Glance: Human skin is a multilayer tissue that covers the human body and works as a barrier between the body and the environment, and it is basically composed of three layers, they are: Epidermis, Dermis and Hypodermis. It is also considered a viscoelastic material due to its mechanical behaviour that obeys mechanical equivalent models under loading and unloading of viscoelastic or polymeric substances [6].

Due to the particular properties of the human skin and Teflon, the friction phenomenon can be explained by its two components, adhesion and deformation, that contribute with a different weightage depending on many factors such as volunteer's age, sex, body part of investigated area of skin or environmental conditions including temperature, relative humidity, applied load(s), etc. to the overall magnitude of the friction.

2. Experimental Setup

The first step in the experimental part of this research is to assure that there is a controlled environment in the laboratory. The environmental conditions maintained over the course of the experiments can be seen in table 3 below:

Table 3. Laboratory room conditions.

	Average Temperature $(°C)$	Humidity %±3	Skin Condition 1	Skin Condition 2	Skin Type	Skin region
Room conditions	25	30	Dry skin	Wet skin	Without marks or scars	Ring finger, ventral intermediate phalanx

The volunteers were asked to provide information about their health status, mainly blood glucose level (HbA1c) Average blood (Haemoglobin) glucose (sugar) levels for the last two to three months and the Body Mass Index (BMI). The gathered data is presented below in table 4.

Table 4. The volunteers' details [6].

	Age (years)	Sex	HbA1c mMol/Mol	HbA1c %	BMI	Ethnicity
Volunteer 1	≈24	male	≈53	7	≈24	Asian
Volunteer 2	≈52	male	≈53	7	≈27	Asian
Volunteer 3	≈66	male	≈60	7.7	≈24	Asian

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2.1. Trace Recovery Time Test by Employing a Pocket Penetrometer

Indentation and residual trace tests are considered an essential examination tool in biotribological tests, where by using these tests the viscoelastic properties of the human skin can be studied.

A pocket penetrometer has been used to check the induced traces in the nominated volunteers. The device used in the tests presented below was a length of 155 mm with a tip diameter of 6.5 mm as shown in figure 1 [7]. A specified pressure of about 5 has been applied vertically on a clean and relaxed region of skin on the three volunteers for one and two minutes respectably and then the skin response as depicted in figure 2 was measured. The results are presented in table 5 below.

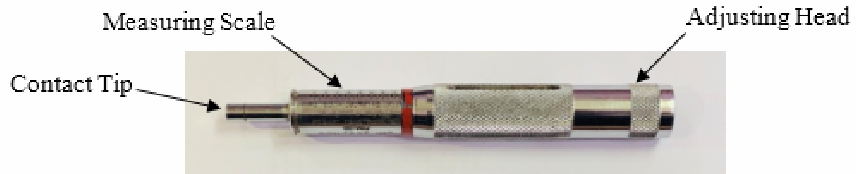

Figure 1. Pocket Penetrometer device.

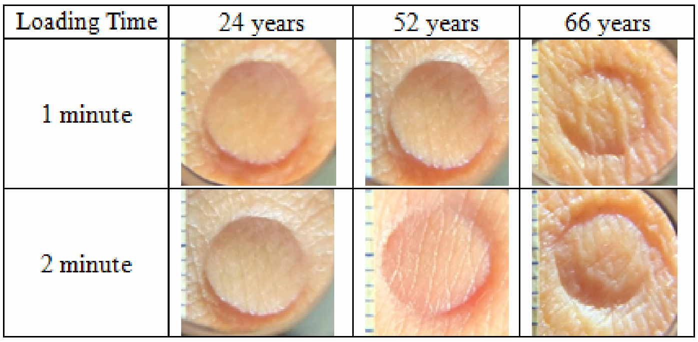

Figure 2. Residual traces of the applied load by the pocket penetrometer.

Table 5. Total trace recovery time.

	Age (years)	Applied pressure (N/cm^2)	Time of loading (minute)	Trace dia. (mm)	Time duration for total trace recovery (minutes)
Volunteer 1	24	5	1	6.4	31
			2	6.7	43
Volunteer 2	52	5	1	6.35	24
			2	6.5	33
Volunteer 3	66	5	1	6.2	19
			2	6.35	27

According to the time dependent nature of the viscoelastic materials, each trace needs a sufficient specific time duration for reaching total trace recovery. As expected, the youngest volunteer needs a relatively long time for the skin to reach the initial condition before the test and the oldest person's skin recovers fastest. Thus, it can be concluded that the time needed to recover decreases with the increase of age.

2.2. Experimental Investigation on CETR-UMT2 Tribometer

In order to complete the essential experimental part of this research investigation, a modern rig has been employed, the CETR-UMT2 Tribometer from the Machine Elements and Tribology Department of University Politehnica Bucharest, [8] depicted in figure 3 below.

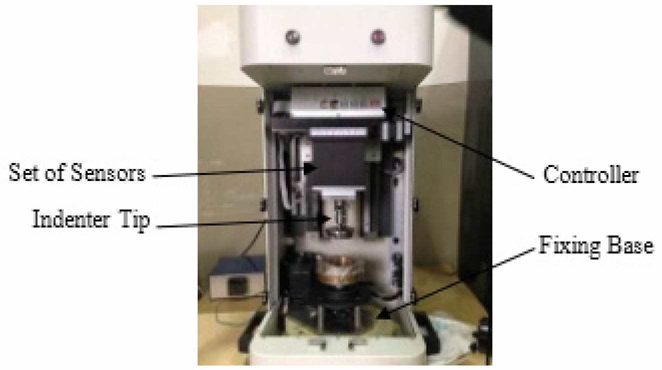

Figure 3. CETR UMT2 Tribometer.

The testing parameters can be seen in table 6 below.

Table 6. The designated boundary conditions, [8].

	Total Applied Load (N)	Maximum Contact Pressure (kPa)	Resolution (µm)	Tip Diameter (mm)
Boundary conditions	(1-12)	≈44	≈1	6.5

The CETR-UMT2 Mechanical Tester and Tribometer is based on the Universal Mechanical Tester (UMT) platform that is most versatile and widely used tribometer currently available. All tests were performed using a polytetrafluoroethylene indenter with a circular cross section and a diameter of 6.5 mm which translates to a cross-sectional area of 33.18 mm^2.

All tests were performed on the same volunteers tested with the pocket penetrometer. The surface of skin to be tested was thoroughly washed with soap and water and both the surface of skin and the indenter were wiped with 70% ethanol solution to ensure the cleanliness of the tested surface.

For each test, a fixture was employed to keep the hand motionless as shown in figure 4 below. After fixing the hand, a designated force of (1-12) N was applied and the tip of the indenter was dragged on the surface of the skin with a velocity of 10 mm/minute, starting from a left side point towards a specified right-side point in order to evaluate the coefficient of friction. The tests were performed 2 times per volunteer, one for the dry case and one for the wet case.

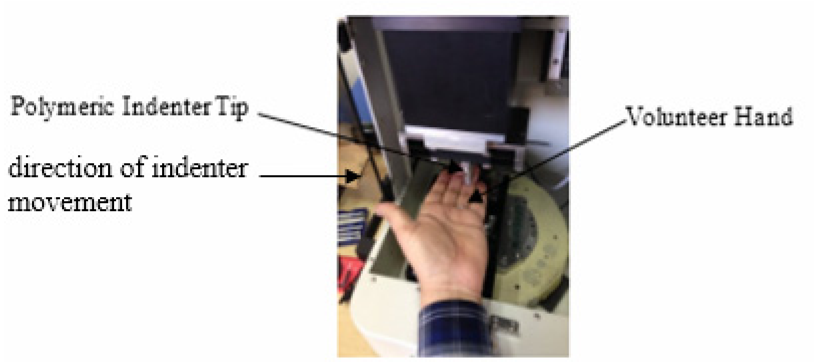

Figure 4. Hand positioning.

3. Experimental Results

Below, in figure 5, the lateral force or friction force can be observed in the case of a dry skin. As a general conclusion, the force stabilizes after approximately 0.5 seconds and its behaviour is fairly similar with all subjects but the friction force decreases with the increase in age of subjects.

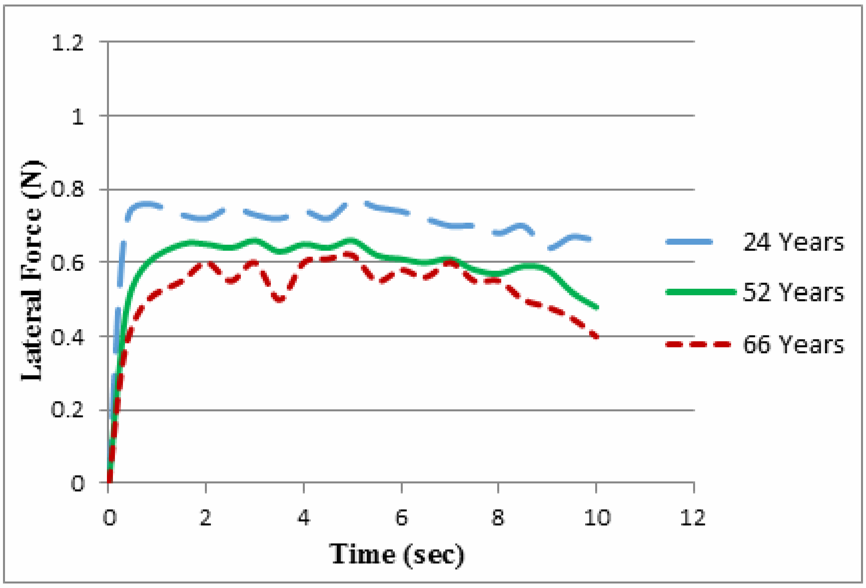

Figure 5. Friction force as a function of time, dry case.

On the other hand, the behavior in the case of a wet skin is completely different. The friction force peaks at 2 seconds and then decreases in magnitude for the remainder of the test. Similarly, to the dry case, the friction force decreases with the increase in age of subjects. This can be seen in figure 6 below.

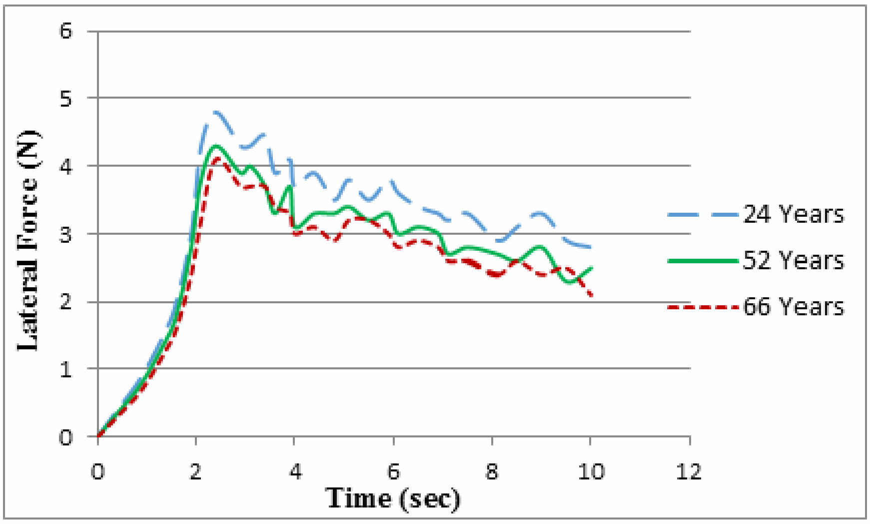

Figure 6. Friction force as a function of time, wet case

Figure 7 gives the expected interaction between the observed coefficient of friction and the corresponding values of the total normal load in the wet case. As stated above, a clear correlation between the age of the person and the coefficient of friction can be drawn. The R^2 correlation parameter values for the three volunteers are 0.9872, 0.9741, and 0.9627 for the 24, 52 and 66 years old respectively show that the experiment the accuracy to be relatively good.

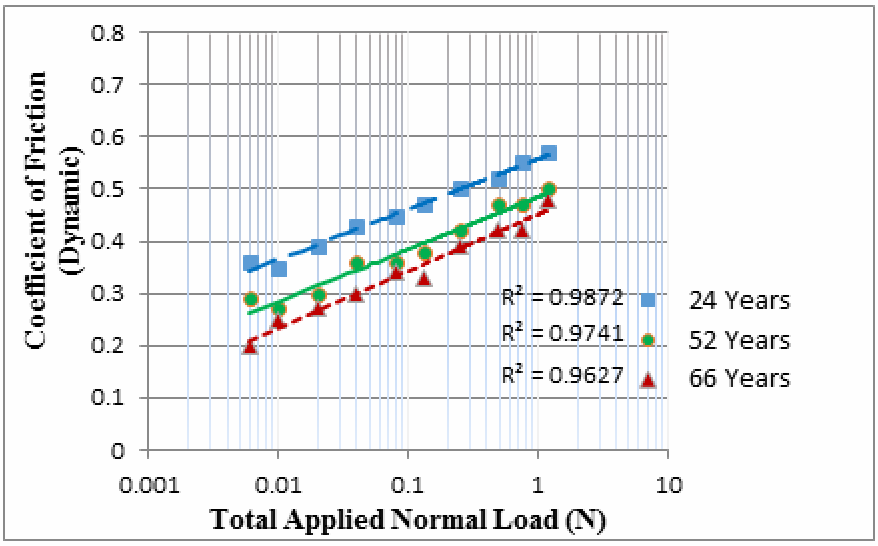

Figure 7. Dynamic coefficient of friction as a function of total applied normal load, wet case.

Figure 8 illustrates the expected behaviour of dynamic frictional force as a function of the applied vertical load in a dry condition for the three volunteers. The proportionality between the two parameters (dynamic force – applied load) is represented by straight line with positive slope in a logarithmic scale, which means that this phenomenon is obeying an exponential mathematical relationship with exponent n, named the load index. This index many be considered as function of the coefficient of friction and the age of the volunteer and consequently the mechanical properties of the layers of human skin. The acquired numerical values in the three equations in figure 8 are showing the proportionality between the load index n as a function of the coefficient of friction and a dependence of the behaviour of the volunteers' skin with age.

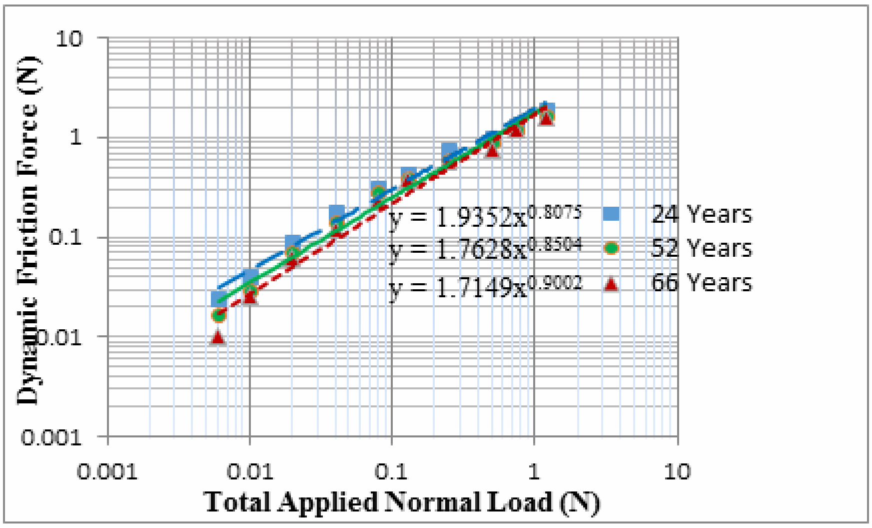

Figure 8. Dynamic coefficient of friction as a function of total applied normal load, dry case.

Now in the wet condition, coefficient of friction exhibits a significant decrease in its value as the total normal load is increased as indicated in figure 9 and in a huge contrast of the dry case in the previous paragraph. This may be attributed to the local formation of the adhesion and deformation components of the main friction force. In addition, the load index n here has a negative value over the assigned time period of the experimental part. The obtained load index is varying from -0.0259 for the

66 years old volunteer to -0.21 for the 24 years old person, meanwhile, the associated value for the 52 years old man is about -0.243, so that is verifying the proposed hypothesis.

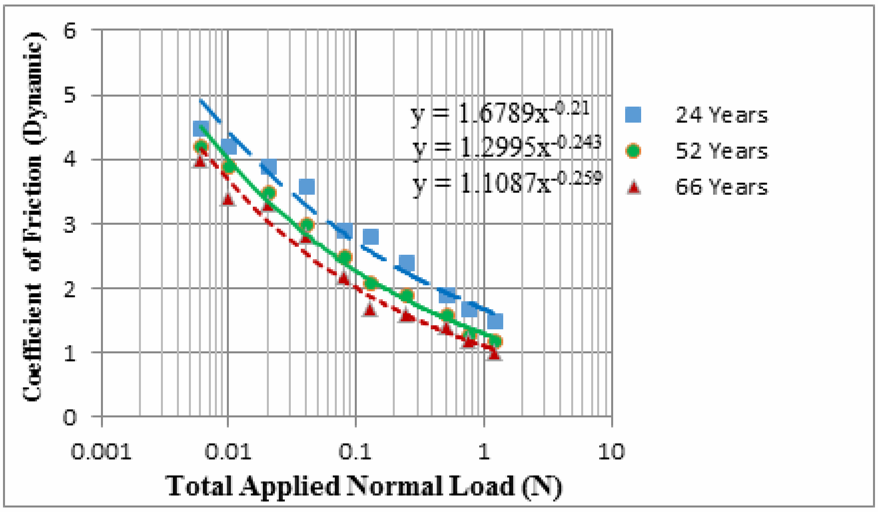

Figure 9. Dynamic coefficient of friction as a function of total applied normal load, wet case.

The wet condition affects the attained value of the frictional force, where these values were higher than the values for dry friction, see figure 10. It is important to mention that the two mating surfaces, the skin and the indenter, are considered to be viscoelastic materials. This means that each surface will sustain a deformation component. The correlation between the friction force and the friction force is directly proportional.

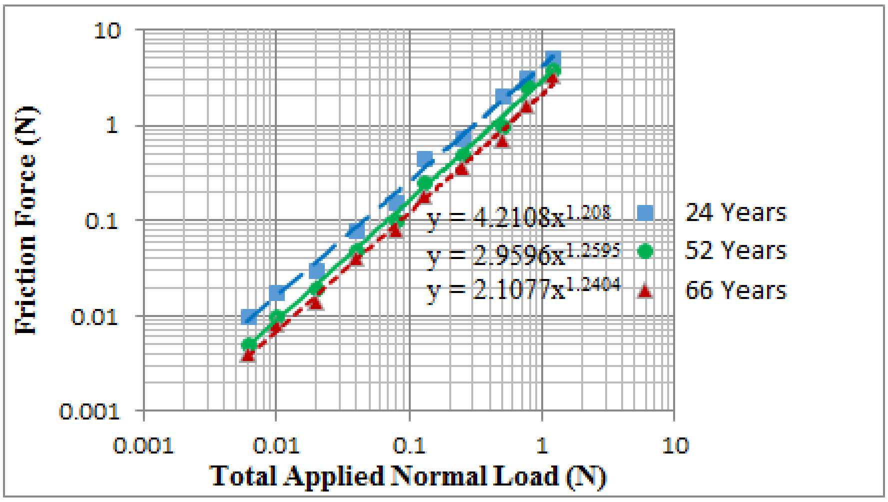

Figure 10. Friction force as a function of total applied normal load, dry case.

At the same time, it is important to measure and examine the friction force between the human hand skin and the employed polytetrafluoroethylene indenter based on the classical theory of friction to at least get an indication about the difference in comparison with the modified theory. Furthermore, it is required to improve grasping quality as a daily ordinary activity of human hand after getting sense about the residual trace of an indenter on human skin as shown in figure 2. Other tests were conducted to measure the static coefficient of friction as a function of the applied normal load, see figure 11. At the starting point, the younger volunteer's skin displays the highest value of the friction coefficient when comparing it with the other two men at the same applied load. This is still valid along a wide range of the applied load with exponential decrement along the experiment span.

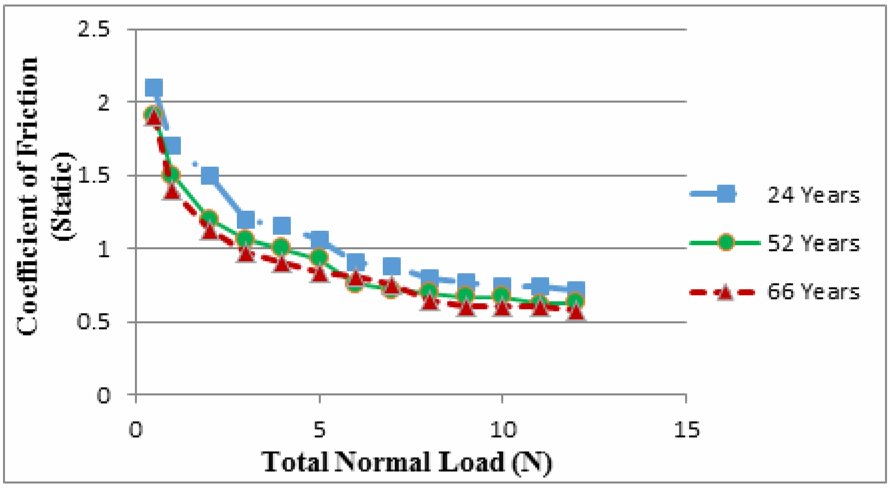

Figure 11. Static coefficient of friction as a function of total normal load.

4. Conclusions

Based on the practical investigation in this paper, the following remarks may be concluded as follows: The frictional interaction of the human hand skin with a polytetrafluoroethylene indenter in a dry state is does not facilitate the formation of adhesive components as it happens in a wet condition, where the local humidity plays an important role in helping the formation of the two components adhesion and deformation.

Another conclusion can be drawn from the age of the subjects. The friction coefficient is greater in the case of a younger subject. In addition, time duration of loading is also having important action, where human skin and the Teflon are both viscoelastic materials and their tribological properties are time dependent. Another important concluded point is: due to specific behaviour of human skin under such tribological loading conditions such in vivo human skin is considered as viscoelastic tissue and exhibits rheological reaction to the applied indentation action.

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