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Artificial Skin Model simulating dry and moist *in vivo* human skin friction and deformation behaviour

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ABSTRACT

In vivo friction and indentation deformation experiments were carried out using the human volar forearm of a healthy 29 year old Caucasian woman and compared with various synthetic materials in order to select materials and develop a new moisture-sensitive Artificial Skin Model (ASM). Analogous to human skin the final ASM comprised two different layers: a relatively stiff hydrophilic moisture-absorbing top layer representing the epidermis and a very soft under-layer representing the dermis and hypodermis. The friction and deformation behaviour of the new ASM were comparable to human skin when tested under dry and moist skin conditions. This development has potential for use as a test-bed in the development of devices that interact with the skin in a mechanical way.

1. Introduction

Skin substitutes are important for clinical use, for example in the management of acute burn injuries and for post burn reconstructions. However, they can also be used as models for experimental testing, for example of healthcare device-patient interfaces, cosmetic skin care devices, electric shavers, etc. In the development of such devices it is often desired to investigate the friction and deformation behaviour of the skin, since these can be important factors for the device function and the perceived comfort during use. Skin hydration is one of the main factors influencing the tribological behaviour of human skin. Moisture commonly increases the skin friction, as is experienced in everyday life, *e.g.* the friction experienced when sliding a moist finger on a touchscreen is much greater than when the finger is dry. In a very humid climate or under wet conditions, the skin becomes completely hydrated, and the friction has been found to be much higher than in dry sliding conditions [1–3]. Unfortunately, friction measurements of devices on human skin *in vivo* have several disadvantages. Such measurements often suffer from poor reproducibility due to person-to-person variability and involuntary human motions occurring during testing. Also, certain experiments are not possible to carry out *in vivo* because they are too damaging to the human tissue. Furthermore, the necessary regulatory approval process for testing on human subjects can increase the development effort and lead-time required. For these reasons, many tribological studies on products involving human skin contact attempt to use mechanical skin equivalents. Synthetic skin substitutes are an alternative that have the potential to provide objective and reproducible results within a reasonable time-frame [4].

There are many skin substitutes available commercially, each of which has been designed with specific purposes and skin characteristics in mind. Examples are: Biobrane™, AlloDerm™, Laser-Skin™, Integra™, TissuFoil™, MatriDerm™, Epidex™, ApliGraft™, Comp Cult Skin™, DermaGraft™, EpiCell™, TransCyte™, OrCel®, Hyalomatrix®, EpiDerm™, EpiSkin™, Cultured Epidermal Autograft (CEA), Cultured Skin Substitutes (CSS). The majority of these were designed to be used in the testing of cosmetic products or for the treatment of skin wounds or burns and attempt predominantly to imitate the biological or histological properties of skin. The mechanical behaviour and textual similarity are often not taken into account [5].

Of the synthetic materials that have been suggested and/or used as mechanical skin substitutes [4,6–24], silicone elastomers and polyurethanes are the most commonly employed materials. Some of these have also been used to simulate the tribological behaviour of human skin under dry conditions. For example, Silicone Skin L7350 is recommended by the Federation Internationale de Football Association (FIFA) for the determination of skin-surface friction of artificial football turf. A major disadvantage of these materials is that they are hydrophobic and unable to absorb sufficient moisture to effectively simulate skin friction behaviour under varying environmental conditions. Use of a material that

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does not absorb water in a moist environment can lead to the formation of a surface film that reduces the friction [4], whereas as mentioned above, human skin absorbs moisture and its friction increases with moisture content until saturated [1,2]. Thus, although silicone elastomers may simulate human skin sufficiently well in the dry condition, they are not capable of simulating the behaviour of moist human skin. The Epidermal Skin Equivalent reported by Morales-Hurtado et al. [24], which is based on a mixture of hydrophobic Polydimethyl Siloxane (PDMS) and hydrophilic Polyvinyl Alcohol (PVA) hydrogel, may show potential in this respect. Although the tribological behaviour was not reported, indentation tests showed that in a 25 °C/50% relative humidity environment the synthetic material had an elastic modulus of approximately 0.7 MPa, within the range reported in the literature for human skin *in vivo*, and that there was a small decrease to 0.5 MPa after the material had been immersed for 4 days in water.

In contrast to human skin, highly porous water-absorbing hydrophilic materials such as SynTissue® from SynDaver™ Labs tend to show a decrease in friction with water content [25]. This is likely due to fluid being squeezed out of the porous structure of the synthetic material, forming a lubricating surface layer [25]. Obviously, fluid cannot be squeezed out of the deeper layers of human skin under load due to the barrier function of the *stratum corneum*. It is necessary to take account of these phenomena in order to develop a skin substitute that simulates the friction behaviour of human skin in both dry and moist conditions.

Structurally, human skin is built up of a number of heterogeneous layers: a very thin upper epidermis layer, with the *stratum corneum* as a stiff outermost layer, a fibre-reinforced dermis layer and an extremely viscous and soft hypodermis layer. The different mechanical properties and individual thicknesses of these layers influence and determine the deformation behaviour of skin and through this, the friction behaviour is influenced [3]. A wide range of values for the elastic modulus and thickness of the various skin layers are reported in the literature [3,25–31] and an overview is given in Table 1 [27].

The current study was aimed at developing an Artificial Skin Model that was capable of mimicking *in vivo* human skin friction behaviour for both dry and moist skin conditions, and which had mechanical properties within the range expected of human skin. To simulate human skin it was decided that the Artificial Skin Model should comprise two layers with very different mechanical properties: a very soft under-layer simulating the dermis and hypodermis, and a stiffer water-absorbing hydrophilic top layer simulating the epidermis.

2. Selection of materials

2.1. Top layer representing epidermis

The uppermost layer of the epidermis (*stratum corneum*) in human skin absorbs water from the external environment. Skin hydration reduces the elasticity and stiffness of human skin (SC, epidermis) typically by one order of magnitude and this strongly influences the friction behaviour. Like human skin, silicone elastomers are viscoelastic materials and can be prepared so as to result in an effective elastic modulus in the range of a few MPa [32], as required for the top layer of the synthetic skin model. However, as mentioned previously, conventional silicone elastomers are hydrophobic and are not able to absorb water, which can lead to a friction behaviour different to actual human skin in moist conditions [4]. Therefore, a new class of hydrophilic silicone rubber that absorbs water was used as the material for the top layer. These silicones are based on standard silicones but modified with strongly hydrophilic alpha-olefin sulphonate. Details on the hydrophilic silicone rubber can be found in patent US 20140113986 A1 and the preparation process adopted for the synthetic skin model is described in Section 3.1.

Table 1
Elastic moduli and thickness of the different layers in human skin [27].

Skin layer, tissue		Elastic modulus, MPa	Thickness, mm
Stratum corneum	*Dry*	500 (3.5–1000)	0.025 (0.01–0.04)
	Wet	30 (10–50)	
Viable epidermis		1.5	0.095 (0.04–0.15)
Dermis		0.02 (8–35 kPa)	1.4 (0.8–2)
Hypodermis		2×10^{-3}	0.8

2.1.1. Water uptake experiments

Two types of experiments were carried out in order to calculate the water uptake capacity of the hydrophilic silicone top layer. In both cases, samples of approximately 5×5 cm and 100 ± 10 µm thickness were first dried in a vacuum oven at 70 °C (< 10 mbar) for 12 h and immediately weighed. The percentage increase in weight was calculated as follows:

Increase in wt% = (Wet Weight − Dry Weight)*100/Dry Weight

The first experiment was carried out in a climatic room in moist conditions (80%Rh and 28 °C) in order to simulate a very humid environment. Mass changes were measured at different time periods, up to 24 h.

A second experiment was carried out where the samples were immersed in distilled water at room temperature and mass changes were measured as a function of time, up to 24 h. For these measurements, the immersed samples were removed at regular intervals and excess surface water was removed using absorbing paper before weighing. After weighing the samples were re-immersed in water.

The results of both experiments are shown in Fig. 1.

The water capacity of the material was determined to be approximately 120% after 24 h immersed in water and about 25% after 24 h in a climatic room at 28 °C and 80%RH, see Fig. 1. Fig. 1 also shows that the water uptake of the hydrophilic silicone is still rising after 24 h, indicating that the material has not yet reached its saturation point.

For comparison, the hydration was also monitored using a Corneometer® which is based on a capacitance measurement and routinely used for assessing the hydration of human skin. Note that this method does not give an absolute value for the water content, however, this method allowed the absolute value of the water content in wt% to be correlated with the hydration value given in arbitrary units (AU), see Fig. 2.

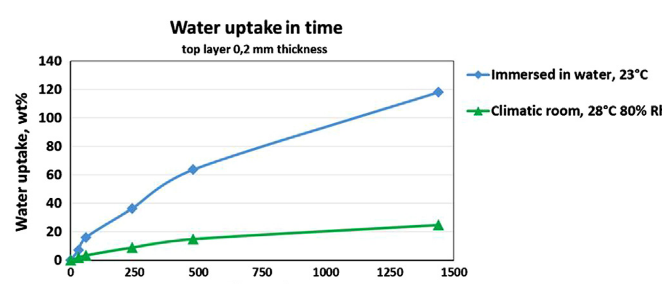

Fig. 1. Water uptake over time of the top layer made of hydrophilic silicone rubber.