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ABSTRACT

The properties of human skin strongly depend on hydration. Skin friction, elasticity and roughness change significantly in the presence of water. This paper presents a new bio-mimicking gelatine-based physical skin model that simulates the frictional behaviour of human skin against a widely-used standard textile under dry and wet conditions and over a broad range of applied normal load (0.5–5 N) and amount of water at the interface (0–100 μl/cm^2). The proposed skin model shows good agreement with the frictional behaviour of human skin both in dry and wet conditions. In addition, the tensile Young's modulus and surface roughness exhibit changes as a function of the amount of water that are similar to those of human skin. Potential applications of the model are in the testing and development of textile materials that mechanically interact with human skin.

1. Introduction

In everyday life, human skin continuously interacts with contacting materials, such as clothes, household items, sports equipment, medical devices, tools and instruments. Therefore, friction between human skin and other objects is a relevant topic of investigations that may not only lead to better ergonomics of these objects but also to the prevention of friction-related injuries, skin disorders or wear [1–3].

Methods to investigate the interaction between the skin and other objects can be divided into two main categories: *in vivo* and *in vitro* measurements. *In vivo* measurements, requiring the involvement of volunteers, can be challenging to perform, expensive and need many test repetitions for statistical significance [4,5]. *In vitro* measurements involve the use of the skin models. There is a wide variety of biological (*e.g.* cell-culture skin models, cadavers or animal skin; porcine, rabbit, rat) or artificial (*e.g.* liquid suspensions, gelatinous substances, elastomers, epoxy resins, textiles or metals) skin models available that could be used in many kinds of investigations, such as cosmetology, drug delivery, biology, and medicine, as well as ballistic, optical or thermal analysis [1,6–9]. Among all possible materials, only a few can be considered to be skin models that mimic the frictional behaviour and friction-related properties of human skin [1,10–12]. Some materials, such as the artificial leather Lorica®, polyurethanes or silicones were found to mimic the frictional behaviour of human skin under specific conditions [2,10,13–16]. However, the existing models show clear limitations. The majority of artificial skin models does not interact with water, whereas ex-vivo (cadavers) or animal skin models need specific storage and preparation procedure and also raise ethical issues [1]. Therefore, there is still a need for a skin model that simulates the frictional behaviour of human skin against everyday materials over a wide range of applied normal load and water amount, providing reliable and accurate results and at the same time being inexpensive and convenient to use and store.

The frictional behaviour of human skin depends on many factors, including factors such as age, gender, health conditions, anatomical region or hydration level [1,17,18]. The roughness as well as mechanical and other properties of the countersurface are also very important [17]. In addition, the frictional behaviour of human skin is strongly influenced by the amount of water in the tribosystem [4,19]. Skin is a multilayer system with a horny upper layer (stratum corneum) that can be considered as a rough and stiff material under normal atmospheric conditions [17,20]. However, hydration of this layer leads to smoothening and softening of the skin, with an associated increase of the real contact area between the skin and other objects, resulting in higher friction coefficient values [2,4,19,21]. A realistic skin model simulating the frictional behaviour of human skin should respond to water in a

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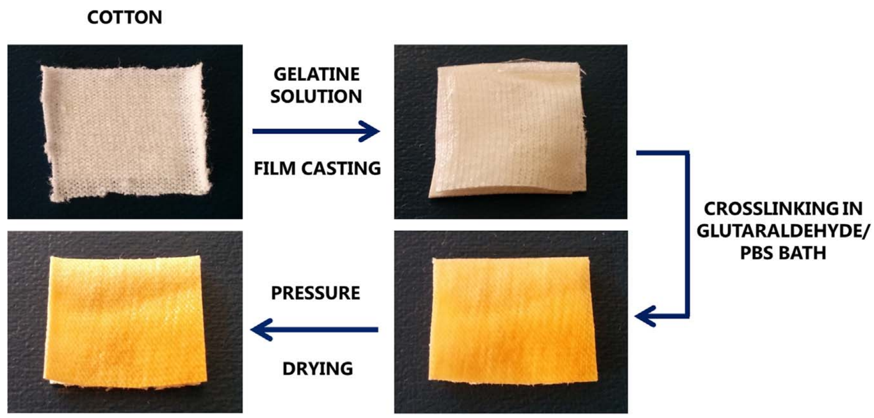

Fig. 1. Preparation procedure of the gelatine-based physical skin model.

similar way.

Gelatine, a proteinaceous product derived from collagen, is known to function as a skin model for many applications. Physical properties of gelatine, such as density, stiffness, sound speed, ballistic performance, energy dissipation, coincide with those of human skin [22–24]. Moreover, it can be made to absorb water without dissolving due to a facile crosslinking process [1,25,26]. The structure of skin itself served as the inspiration for the proposed physical model, the collagen and elastin fibers of the natural material being mimicked by a cotton-based textile, while the gelatine simulated the function of other components of the extracellular matrix [27,28].

The new physical skin model not only simulates the frictional behaviour of human skin against a standard textile in dry and hydrated conditions over the entire range of applied normal load (0.5–5 N), but it also mimics the skin-specific change in the tensile Young's modulus and surface roughness caused by water uptake.

2. Materials and methods

2.1. Preparation of the skin model

Fig. 1 shows schematically the preparation procedure of the gelatine-based skin model. In a first step, with the use of a bar coater (Coatmaster 509 MC, Erichstein), a 10 wt% solution of gelatine (type A, bloom no 300, Sigma Aldrich) in distilled water (prepared by continuous stirring at 60 °C for 2 h) was spread on top of knitted cotton fabric in three layers of 300 µm and left to dry for 24 h at room temperature after the application of each layer. The knitted cotton was selected to be the bottom layer after preliminary tests, including six other textiles, as the skin model containing this substrate displayed frictional behaviour closest to human skin. The resulting composite material was then placed in 1 wt% solution of glutaraldehyde (Sigma Aldrich) in Dulbecco's PBS buffer (DPBS, GIBCO) for 24 h at room temperature under continuous gentle stirring (130 rpm) in order to crosslink the gelatine. In the next step, the crosslinked skin model was rinsed with distilled water and slowly dried by wrapping in paper towels and squeezing between two boards with the use of a 4 kg weight, in order to avoid ripples caused by drying-related contraction. The paper towels were changed every day and the skin model was considered to be dry after about 6 days, at which point the mass had stabilized.

2.2. Friction measurements

In order to determine whether the model mimics the frictional behaviour of human skin, identical procedures were used for both *in vivo* and *in vitro* friction measurements. Martindale test fabric (worsted wool cloth) was used as a reference textile. Measurements were performed in three different moisture states: dry and two hydrated conditions (moist and wet). In the case of dry conditions, samples were stored under ambient environmental conditions at a temperature of approximately 20 °C without any further addition of water. Moist conditions, simulating physiological sweat accumulation, were achieved by distributing to 10 µl distilled water per 1 cm^2 [29]. Wet conditions corresponded to the maximum water uptake of the textile (21.6 $\mu l/cm^2$ for the Martindale fabric), measured as a weight difference between the sample of the Martindale fabric before and after immersion in water. Besides these specific conditions, friction coefficients of the skin and the skin model were investigated as a function of the amount of water in the range of 0–100 $\mu l/cm^2$ in the reference textile.

2.2.1. In vivo *friction measurements*

The *in vivo* study was approved by the Ethics Committee of the Kanton St. Gallen (EKSG 13/156/1B). All measurements were performed in an environmentally controlled room at 23 ± 1 °C temperature and relative humidity of 50 ± 2%. *In vivo* measurements were performed on the volar forearm, which can also be considered as representative of certain other skin areas. Furthermore, it is located in a relatively flat anatomical region, which makes measurements easier and provides better reproducibility [17].

In vivo measurements of the friction coefficient of the skin against Martindale fabric were performed as a function of the applied normal load on the right forearm of 6 healthy volunteers (3 men and 3 women with the average age of 27 ± 4.5 years and with the average Body Mass Index (BMI) of 23 ± 2.8) [30]. Friction-coefficient measurements were also performed against the Martindale reference textile as a function of the amount of water on the right forearm of one healthy male volunteer aged 36 years with a BMI of 28. For each investigated condition, volunteers were asked to rub their forearms against the reference textile at least ten times, consciously controlling and modulating the applied load. The textile was fixed on a three-axis force plate (Kistler 9254) [2].

2.2.2. In vitro *friction measurements*

The frictional behaviour of the gelatine-based skin model against Martindale fabric was investigated in an environmentally controlled room (20 ± 1 °C, 65 ± 2% RH) by means of a purpose-built textile friction analyzer (TFA) [3]. Measurements were carried out with a frequency of 1.25 Hz over a distance of 50 mm for 350 cycles for each applied load. Additional experiments, concerning running in (applied load: 0.5 N) were performed under hydrated conditions until a stabilization of the friction coefficient was observed. Three independent series of measurements were performed, in order to calculate average values. Fig. 2 shows representative results for the running-in process.

2.3. Determination of the Young's modulus

The Young's modulus of the dry and hydrated (immersed in distilled water for 20–60 min) gelatine-based physical skin model

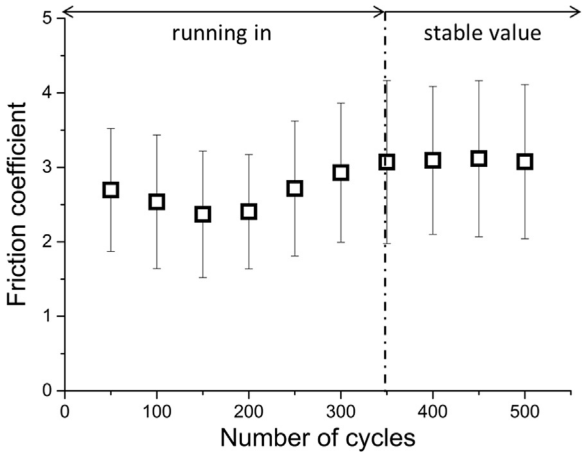

Fig. 2. Representative running in process for the skin model rubbed against Martindale under moist conditions.

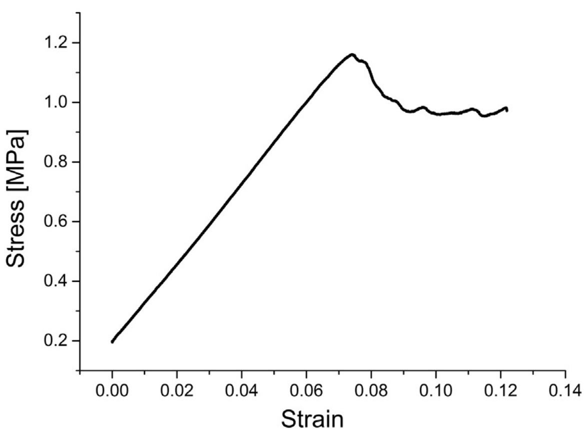

Fig. 3. Representative stress-strain curve for the skin model immersed in water for 15 min before the measurement.

was evaluated in an environmentally controlled room (23 ± 2 °C, 50 ± 10% RH) using a Zwick Roell Biaxial Testing Machine (Zwick-Roell GmbH Ulm, Germany) with optical strain measurement. Dry and hydrated samples with average dimensions of 40×5.5×0.45 mm were tested at a speed of 1 mm/min and a 0.5 N preload was applied. The value of Young's modulus was obtained from the slope of the measured stress-strain curve, up to 1% strain. Three independent series of measurements were performed. Fig. 3 shows the nominal stress as a function of nominal strain for a representative sample previously immersed in water for 15 min.

2.4. Structural and surface characterization

Microscopic techniques were used to investigate the structure, surface morphology as well as the water response of the gelatine-based skin model.

The cross-section of the skin model was observed by means of scanning electron microscopy (SEM) (Hitachi S-4800, Japan) at 10 mA beam current and 2 kV accelerating voltage. Samples were plasma coated with a 5 nm Au/Pd layer before the measurement (Leica Microsystems EM ACE 600, Germany).

The surface of the gelatine-based skin model was observed before and after 20 min immersion in distilled water by means of a 3D Laser Scanning Confocal Microscope, model VK-X250 (Keyence, Osaka, Japan), equipped with a violet laser (λ=408 nm). Each sample was analyzed at three different spots using a 20× objective lens. The surface roughness parameters Sa and Sz were extracted using VK-H1XME (VK-X AI-Analyzer Software, Osaka, Japan). All artefacts and characteristic surface features were avoided during subsequent data processing.

The water contact angle of the cotton substrate was measured by means of a drop shape analyzer (DSA25, Krüss, Germany).

The thickness of the skin-model samples was measured by means of the Tesa Isomaster caliper with analogue readout. Measurements were performed for dry and hydrated (immersed in water for 20 min) skin models and repeated 10 times for each sample. Measurements were repeated on three independent samples both under dry and hydrated conditions and the average value was calculated. Before the actual measurement series, preliminary measurements indicating the immersion time for the maximum change in thickness were performed.

3. Results and discussion

3.1. Frictional behaviour of human skin and the skin model

Average friction coefficient (COF) values, calculated as the average values for the whole range of the normal load (0.5–5 N), for skin and the skin model rubbed against Martindale fabric in dry, moist and wet conditions, are given in Fig. 4.

No statistically significant difference has been observed between the average friction coefficient values reported for human skin and for the skin model under dry, moist and wet conditions (p values, accordingly: 0.25, 0.35, 0.97).

Based on the results of *in vivo* measurements, it can be observed that the friction coefficient values increased when water was applied at the interface between the skin and the reference textile. This observation is consistent with the adhesion theory of human skin friction [19,21]. As skin is exposed to water, it becomes softer and easily deformable, what causes a higher real contact area between the skin and counterfaces [19,20]. The value of the tensile Young's modulus of the skin is strongly influenced by the presence of water, which is evident for the stratum corneum, the tensile Young's modulus value falling in the range of GPa for RH=30% and decreasing into the range of MPa when humidity increases to 100% RH [31–38]. In addition to decreased Young's modulus values, the plasticizing effect of water on human skin leads to smaller surface roughness values [21,39,40]. The role of the textile in the investigated system cannot be neglected. As cotton-based textiles frequently respond to the presence of water by becoming swollen and plasticized, the effect of water will be particularly strong in the skin/textile tribological system [41,42]. Lower surface roughness values and easier deformation for both the skin and the textile contribute to an increased real contact area and thus increased friction coefficient [43].

Fig. 5 shows the results of the friction measurements for human skin and the skin model against Martindale fabric as a function of the

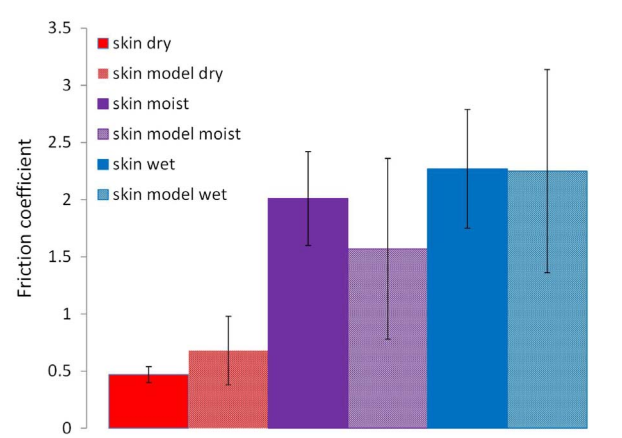

Fig. 4. Average friction coefficients for human skin and the skin model rubbed against Martindale fabric in dry, moist and wet conditions.

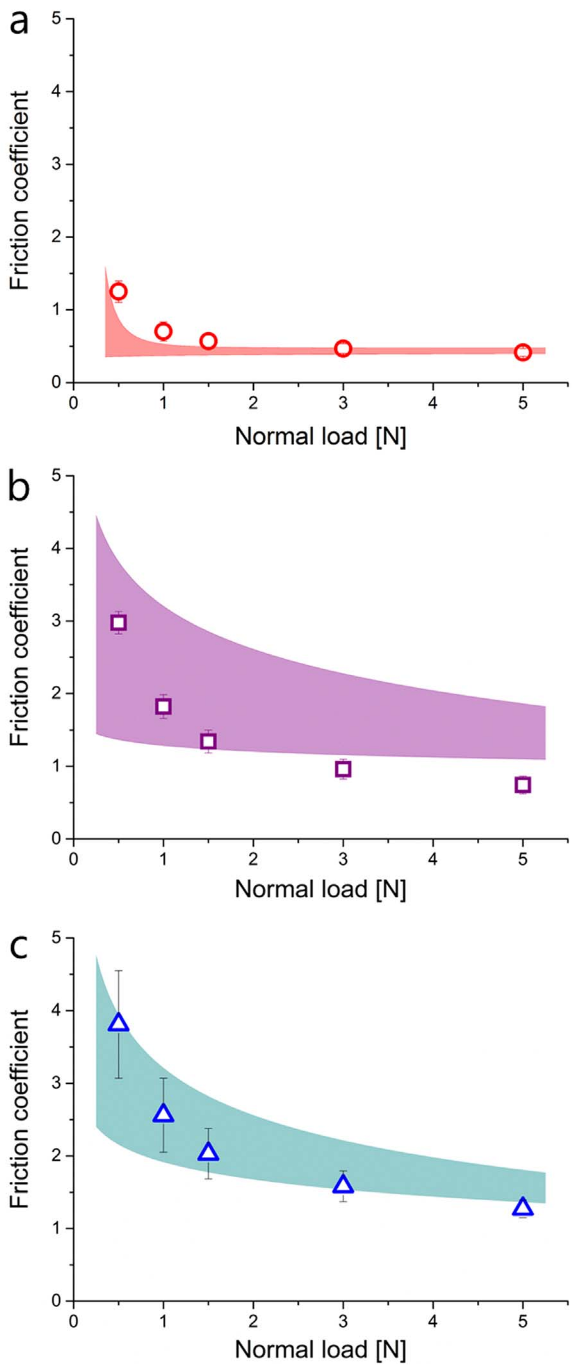

Fig. 5. COF of human skin (range of the values measured for the skin; shaded area) and the skin model (markers) against Martindale fabric as a function of the normal load in dry (a), moist (b) and wet (c) conditions.

applied load under dry (Fig. 5a), moist (Fig. 5b) and wet (Fig. 5c) conditions.

As human skin is a very complex, anisotropic tissue with properties influenced by many factors, such as age, gender, ethnicity, health, lifestyle or physiological conditions, friction coefficient values of skin are given as a value range instead of the single values due to high standard deviations [1,17]. As presented by Adams et al. [19], the COF of dry skin, consistent with the conventional definition, can be understood as a constant value. Our results can in general support this statement, at normal loads below 1 N. The presence of water between skin and the counter-material changes the interfacial conditions significantly. The COF values not only increase, as mentioned above, but also depend on the normal load [19,44–46]. The contact area of

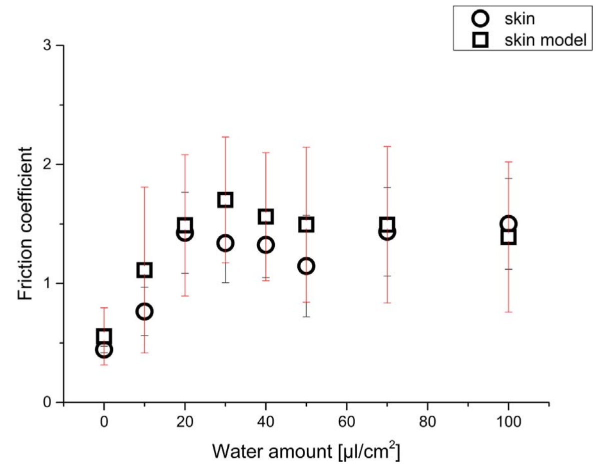

Fig. 6. COF of the gelatine-based skin model and of human skin against Martindale fabric as a function of the amount of applied water. Friction coefficient values are averaged for the entire range of normal load (0.5–5 N).

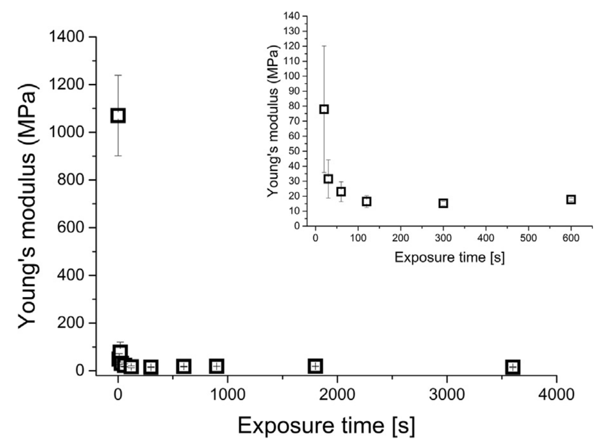

Fig. 7. Young's modulus of the gelatine-based skin model before and after water exposure. Inset: Influence of short water exposure (20–600 s) on the Young's modulus value.

skin is not directly proportional to the normal load, but increases as a function of the normal load until it reaches a plateau. The COF decreases with increasing normal load, reaching a plateau for normal load values of 5 N and higher [47–49].

Another view of the characteristic frictional behaviour of human skin is presented in Fig. 6. The average COF values for the entire range of applied load (0.5–5 N) are plotted as a function of the amount of water applied between skin and the textile and compared with corresponding COF values for the investigated gelatine-based composite material.

As previously discussed by Derler et al. [50], the COF of human skin, due to the hydration and capillary adhesion, initially increases as a function of the amount of water present in the system and decreases again after passing through a maximum value, as excess water creates lubricated regions leading to lower COF values.

The comparison between ranges of COF values obtained through *in vivo* measurements performed on skin of the volar forearm and COF values obtained for the gelatine-based composite material through *in vitro* measurements performed under similar conditions (Figs. 5 and 6) suggests that the studied material is suitable as a physical skin model to simulate the frictional behaviour of human skin. The gelatine-based skin model is able to mimic the frictional behaviour of human skin against Martindale fabric over the entire range of investigated normal loads and in the presence of various amounts of water in the system. The COF of the skin model increases in the presence of a moderate amount of water (compared to dry conditions) and decreases as a

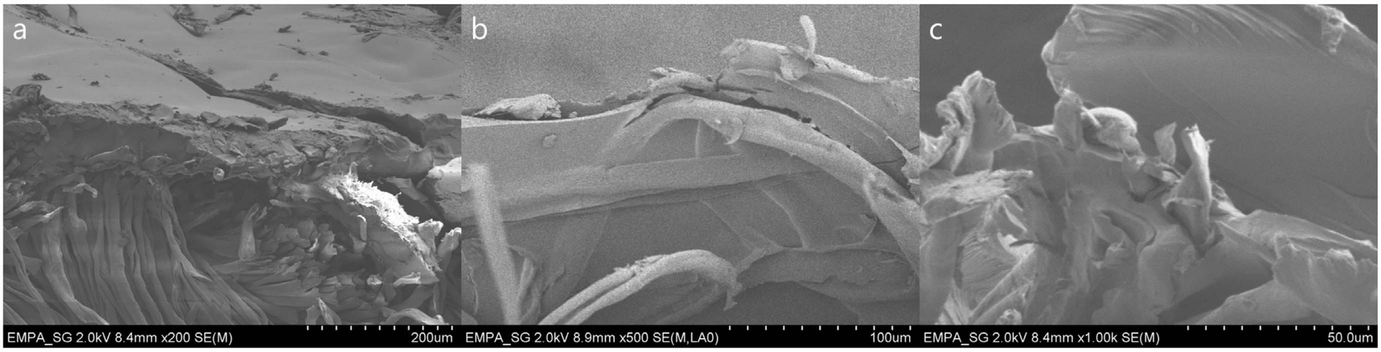

Fig. 8. SEM images of a cross-section of the gelatine-based physical skin model at 200× (a), 500× (b) and 1000× (c) magnification.

function of the normal load, following the general trend and values reported for human skin (Fig. 5). When the influence of increasing amount of water on the COF values is investigated, the gelatine-based skin model mimics human skin according to general trends and COF values as well (Fig. 6).

3.2. Tensile Young's modulus

The change in the Young's modulus of the gelatine-based skin model after up to 1 h water exposure was investigated (Fig. 7).

In analogy to human skin, hydration changed the stiffness of the investigated skin model significantly. The Young's modulus of the dry material reached a range between 0.9 and 1.2 GPa, whereas following brief immersion in water (20 s) it dropped to 78 ± 42 MPa and decreased further to 15.8 ± 1.8 MPa for longer (1 h) immersion time, showing a decrease by three orders of magnitude. After around 100 s exposure time there is no further clear influence of the increasing water content on Young's modulus values.

3.3. Structural and surface characterization

Fig. 8 shows the cross-section micrographs of the gelatine-based skin model measured by means of SEM with 200× (Fig. 8a), 500× (Fig. 8b) and 1000× (Fig. 8c) magnification. The knitted cotton, used as a substrate, is hydrophobic (WCA: 131 ± 5°) and hygroscopic, therefore it absorbs parts of the water-based gelatine solution during the process of bar coating. SEM pictures of a cross-section of the prepared skin model (Fig. 8) show that some cotton fibers are embedded in the gelatine coating. This leads to a high degree of cohesion and therefore results in a robust and non-delaminating material.

Water acts as plasticizer in human skin, leading not only to a decrease in stiffness, but also to a smoother surface. It was shown that the surface roughness of human skin decreases significantly after exposure to water [21,39,40]. In order to compare the specific water response of human skin with the gelatine-based physical skin model, a similar surface analysis was carried out.

The dry gelatine-based skin model is a stiff material with a ridged structure. When exposed to water, as both crosslinked gelatine and cotton absorb water, it became soft, flattened and smoothened, which was observed as a significant decrease in the measured surface roughness parameters; Sa decreases from 2.3 ± 0.3 μm for dry to 0.8 ± 0.1 μm for hydrated conditions (analogically, Sz decreased from 74.8 ± 13.5 μm to 8.6 ± 2.5 μm). Fig. 9 shows three-dimensional microscopic pictures of the skin model before (Fig. 9a) and after (Fig. 9c) water exposure and the influence of the water exposure on the surface roughness parameters Sa (Fig. 9b) and Sz (Fig. 9d).

Due to water uptake and swelling, the *stratum corneum* thickness increases after prolonged water exposure [51–53]. Our recent study [52] showed that the maximum increase in the *stratum corneum* thickness was equal to 21% and was observed after 60 min of one-sided water exposure.

The maximum increase in thickness of the gelatine-based skin model was observed after 20 min of full immersion in water. Similarly to the *stratum corneum*, the thickness of the skin model also increased by 21% (from 0.66 ± 0.10 mm for dry skin model to 0.79 ± 0.11 after 20 min immersion in water, $p=7\times10^{-6}$). Fig. 10 shows the change in

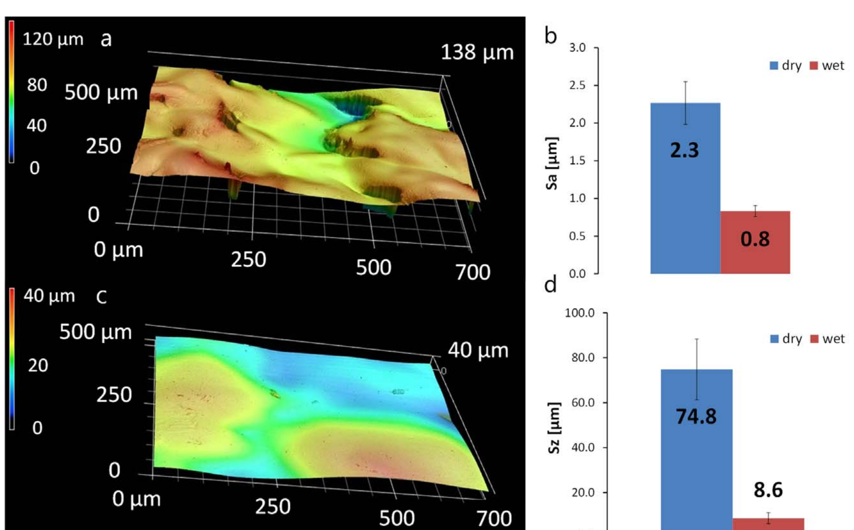

Fig. 9. Influence of water on the surface morphology of the gelatine-based physical skin model. Three-dimensional optical microscopic images of the gelatine-based physical skin model in the dry (a) and hydrated (c) state. Sa (b) and Sz (d) of the skin model in the dry and hydrated state.

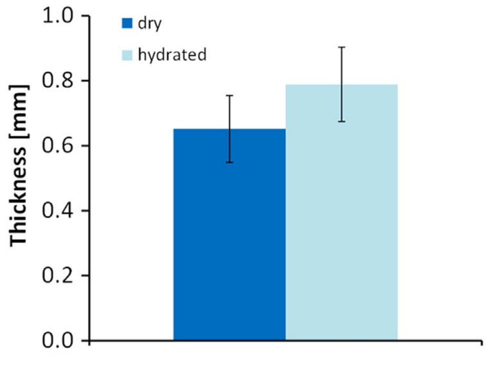

Fig. 10. Change in thickness of the gelatine-based skin model after 20-min immersion in water.

thickness of the examined skin model after 20 min of water immersion.

The gelatine-based skin model displays some limitations and has potential for further development. The proposed model is at present a single-use material, for example.

4. Conclusions

A new gelatine-based physical skin model was prepared and characterized regarding its frictional behaviour when in contact with a standard textile (Martindale fabric, worsted wool cloth) under both dry and hydrated conditions as well as with respect to the influence of water on the tensile Young's modulus and surface morphology. Friction coefficients for the skin model rubbed against Martindale fabric lie within the range of the values measured for human skin (volar forearm) under corresponding conditions over the entire range of investigated applied normal load. The gelatine-based skin model shows a similar behaviour to human skin when exposed to water, resulting in a significant decrease in the tensile Young's modulus value (from the GPa to the MPa range), surface smoothening and increase in thickness. Both observed phenomena were in accordance with literature reports [20,33]. The new physical skin model mimics the general trends and values that are characteristic of the frictional behaviour, Young's modulus, change in thickness and surface morphology of human skin. Therefore, this material can potentially be used as a substitute for, or supplement to, conventional *in vivo* friction measurements, providing information concerning the interaction between human skin and examined objects.

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