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A water-responsive, gelatine-based human skin model

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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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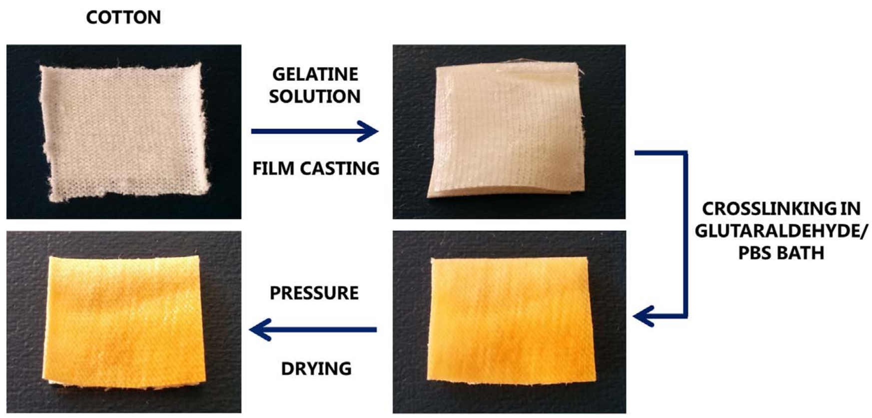

Fig. 1. Preparation procedure of the gelatine-based physical skin model.

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