Interpretation of the human skin biotribological behaviour after tape stripping

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The present study deals with the modification of the human skin biotribological behaviour after tape stripping. The tape-stripping procedure consists in the sequential application and removal of adhesive tapes on the skin surface in order to remove stratum corneum (SC) layers, which electrically charges the skin surface. The skin electric charges generated by tape stripping highly change the skin friction behaviour by increasing the adhesion component of the skin friction coefficient. It has been proposed to rewrite the friction adhesion component as the sum of two terms: the first classical adhesion term depending on the intrinsic shear strength, $\tau_0$, and the second term depending on the electric shear strength, $\tau_{\text{elec}}$. The experimental results allowed to estimate a numerical value of the electric shear strength $\tau_{\text{elec}}$.

Moreover, a plan capacitor model with a dielectric material inside was used to modelize the experimental system. This physical model permitted to evaluate the friction electric force and the electric shear strength values to calculate the skin friction coefficient after the tape stripping. The comparison between the experimental and the theoretical value of the skin friction coefficient after the tape stripping has shown the importance of the electric charges on skin biotribological behaviour. The static electric charges produced by tape stripping on the skin surface are probably able to highly modify the interaction of formulations with the skin surface and their spreading properties. This phenomenon, generally overlooked, should be taken into consideration as it could be involved in alteration of drug absorption.

Keywords: biotribology; electric charge; friction model; stratum corneum; tribo-electricity; tape stripping

1. INTRODUCTION

Human skin is a stratified tissue composed of three different layers, which are from the bottom to the top: hypodermis, dermis and epidermis. The outermost layer of epidermis, called stratum corneum (SC), arises from the sequential differentiation of cells migrating from the basal epidermal layer to the surface. The SC consists of about 15 tightly stacked layers of flattened dead cells full of keratin, embedded in a lipidic intercellular matrix, mainly composed of ceramides, long-chain free fatty acids and cholesterol [1]. The water content of the SC is low, compared with viable tissues, and it is characterized by a gradient that increases from the skin surface to the viable epidermis [2–7]. Due to its peculiar structure and composition, the SC represents the main barrier against the penetration of exogenous substances and also against transepidermal water loss.

Tape stripping is a minimally invasive procedure for the removal and sampling of SC. It consists in the sequential application and removal of adhesive tapes onto the skin surface, in order to collect microscopic layers of SC. Since skin stripping results in barrier disruption, this procedure is used, besides other applications, as an in vivo model for those skin diseases characterized by skin barrier weakening; for the same reason, it can be used to evaluate the effect of the application of skin care products on barrier restoration [8–10].

The SC, despite its limited thickness (between 10 and 20 µm), and even if its mechanical properties are very different from those of viable skin [11–14], is the layer that mainly controls the skin biotribological behaviour [12]; it follows that the removal of this layer

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(for instance by tape stripping) will dramatically affect them. Moreover, the static electric charges produced by tape stripping on the skin surface, are probably able to modify the interaction of formulations with the skin surface and their spreading properties. This phenomenon, generally overlooked, should be taken into consideration as it may be involved in alteration of drug absorption.

The aim of this paper is to propose a new method to describe and explain the skin tribological behaviour in vivo after the tape-stripping procedure. In this study an original method is proposed to estimate the surface electric charge produced by tape stripping on the skin surface based on a tribological analysis.

In fact, because of the production of electric charges on the skin surface, the skin friction coefficient is highly modified, especially the adhesion component of the friction coefficient. To explain this modification, a new assumption about the classical friction law has been made. It consists in inserting into the adhesion component of the friction force an electric shear strength term, \( \tau_{elec} \), due to the electric charges on the skin surface. The value of the electric charge on the skin surface has been measured using a fieldmeter device and the electric shear strength has been experimentally estimated. The experimental value of the electric shear strength has been compared with the theoretical value obtained with a physical model consisting in a plan capacitor with dielectric material inside.

2. MATERIAL AND METHODS

2.1. Bio-tribometer device and measurement of electric charges

The use of an original light load indentation/friction device to study the mechanical and tribological properties of human skin in vivo has been previously reported [15]. Traditionally, the indentation test consists in recording the penetration depth, \( \delta \), of a rigid indenter as a function of the applied normal load, \( F_z \), during a loading/unloading experiment. The friction test consists in applying a constant normal load and sliding velocity on the skin surface and in measuring the resulting friction force, \( F_x \). In the present study, the indentation/friction tests are performed in controlled displacement mode. The displacement is obtained from the National Instrument displacement tables and controlled by a displacement sensor (figure 1a). The indentation tests are realized with the z-displacement table, whereas the z-displacement table enables the friction tests. The maximum displacement during the loading/unloading cycle can reach about 15 mm with a resolution of 10 \( \mu \)m, and the experimental device offers a wide range of indenting/sliding velocities from 5 to 1500 \( \mu \)m s\(^{-1}\). In the present paper, the normal load was applied for a constant indentation speed \( \dot{\delta} = 400 \mu \)m s\(^{-1}\) and friction tests were performed for a constant friction velocity \( V = 400 \mu \)m s\(^{-1}\). The used probe was a spherical steel probe, with a radius of curvature \( R = 6.35 \) mm.

The electric charge value on the skin surface was measured by using a fieldmeter device (JCI 140 Static Monitor). It is a compact sensitive ‘field mill’ instrument to measure the voltage of surfaces at a distance \( h \). The fieldmeter is fixed on a z-displacement table to control the distance, \( h \), between the charged skin surface and the fieldmeter device (figure 1b). All the measurements were performed using \( h = 1 \) mm.

2.2. In vivo skin indentation/friction test

The friction tests were carried out on the inner forearm, at 5 cm from the elbow, of three healthy Caucasian women, from 28 to 34 years old. This location is easily accessed, relatively flat and there are few disturbances by the natural movements of the body. In order to facilitate reading of the results, the results of a unique volunteer, which approximately correspond to average behaviour among the three volunteers, will be chosen to illustrate the analysis. The tests were made at controlled temperature (22–24°C) and relative humidity (20–30%).

The tests were carried out in controlled normal load, which will allow us to include all the adhesion effects within the normal load (adhesion, electric charges effect, etc.).

All tests were repeated five times for each subject.

2.3. Tape-stripping test

Tape stripping is a minimally invasive procedure for SC removal and sampling. It consists in the sequential application and removal of an adhesive tape-strip onto the skin surface, in order to collect microscopic layers (0.2–1 \( \mu \)m) of SC [16,17] (figure 2).

Scotch 3M, precut to 1.9 cm \( \times \) 2.5 cm, was used to realize the tape stripping. To estimate the quantity of the SC removed, each tape was weighed before and after the tape-stripping test. The mass variation obtained, \( \Delta m \), corresponds to the mass of SC removed by each tape. The average thickness of the SC removed, \( e \), was then calculated from the cumulative mass and the density of the SC, \( \rho_{SC} \), from 1 to 1.33 g cm\(^{-3}\) [2,18] (figure 3). The evolution of the thickness of the SC removed from each tape stripping is reported in figure 3.
negligible compared with the interfacial adhesion term considering that

\[ F_{\text{int}} = \frac{\tau_0 A}{p} + \alpha. \quad (3.2) \]

4. RESULTS AND DISCUSSION

4.1. Analysis of the skin friction force curve as a function of the thickness of the removed stratum corneum

The variation of the skin friction force as a function of the amount of SC removed has been studied (figure 4). The obtained results indicate that the skin friction force and the amplitude of stick-slip phenomena greatly increase when removing layers of SC. The lateral stiffness, which corresponds to the slope of the friction curve in the sticky zone, decreases after the tape-stripping procedure, as previously observed in the literature [12]. Moreover, the distance necessary before the sliding phase between the skin and the steel spherical probe increases after the tape stripping. These substantial modifications of cutaneous friction force are explained by an increase in the adhesion force between the skin and the probe [12], which is due to a relevant change of the skin physico-chemical surface properties. To understand the interfacial skin property modifications after the tape stripping, wettability tests were realized with distilled water on the skin-stripped zone. The wettability tests were realized with the ‘pocket goniometer’. To measure the contact angle, a camera is integrated to the ‘pocket goniometer’. The volume of water micro-droplets placed onto skin surface was 1.5 μl. The contact angles between the distilled water and the skin surface were measured before (TS = 0) and after five (TS = 5) tape stripings (figure 4). The values of the contact angles measured before the tape stripping (TS = 0) \( \theta_s = 91^\circ \) confirm the values previously observed in the literature [25–27]. However, the shape of the distilled water micro-droplet after five tape stripings (TS = 5) \( \theta_s = 132^\circ \) are not in good agreement with the water gradient inside the epidermis [2–7]. The contact angle between the stripped skin and the distilled water should decrease, contrary to what is observed (figure 4).

To explain the distorted micro-droplet shape and the skin friction force behaviour after tape stripping, the voltage between the fieldmeter device and the surface skin was measured as a function of time and for different tape-stripping values (figure 5). All the measurements were realized for a distance \( h = 1 \) mm (\( h \) is the distance between the fieldmeter device and the surface skin). The obtained voltage values are practically constant whatever the thickness of the removed SC. The average value of the voltage is between 4 and 5 kV. Small variations in the voltage are mainly due to the natural movement of the forearm during the measurements.

4.2. New assumption about skin friction theory

The increase in the skin friction force after tape stripping may be due to the electrical phenomenon at the
To evaluate experimentally the electric shear strength, the friction force may increase the adhesion component of the skin interface between skin and probe. Electric charges may increase the adhesion component of the skin friction force. As a consequence, the friction force (3.1) can be re-written by adding an electric shear strength, \( \tau_{\text{elec}} \), as

\[
F_z = F_{\text{int}} = (\tau_0 + \tau_{\text{elec}})A + \alpha pA. \tag{4.1}
\]

This means that the friction coefficient can be re-written as

\[
\mu = \frac{(\tau_0 + \tau_{\text{elec}})}{p} + \alpha. \tag{4.2}
\]

### 4.3. Experimental estimation of the electric shear strength

To evaluate experimentally the electric shear strength, \( \tau_{\text{elec}} \), the variation of the friction coefficient as a function of the inverse of the contact pressure has been reported in figure 6. The contact pressure is the average contact pressure, \( p \), and it has been calculated with the Hertzian theory [28] for a measured skin reduced Young’s modulus from 10 kPa to 14 kPa as a function of penetration depth [11], as

\[
p = \frac{1}{\pi} \left( \frac{16 E^2 F_z}{9 R^2} \right)^{1/3}, \tag{4.3}
\]

where \( E^s \) is the measured skin reduced Young’s modulus, \( F_z \) is the normal load and \( R \) is the radius of curvature of the spherical probe equal to 6.35 mm.

The results indicate that the skin friction coefficient increases as a function of the inverse of the contact pressure before and after the tape-stripping procedure. The intrinsic shear strength, \( \tau_0 \), and the electric shear strength, \( \tau_{\text{elec}} \), were calculated using equations (3.2) and (4.2). The intrinsic shear strength, \( \tau_0 \), which is the slope of the curve before the tape stripping (figure 6), was calculated on the curve before the tape stripping with equation (3.2): \( \tau_0 = 0.38 \text{ kPa} \). The electric shear strength, \( \tau_{\text{elec}} \), was obtained with the curve after five tape strippings (figure 6). The slope of the curve after five tape strippings is \( \tau_0 + \tau_{\text{elec}} \) and it is equal to 1.35 kPa; therefore, the value of the electric shear strength is \( \tau_{\text{elec}} = 1.35 - \tau_0 = 0.97 \text{ kPa} \).

The small variation in the \( \alpha \) parameter is probably due to the modification of the skin surface roughness after tape stripping [29].

### 4.4. Theoretical estimation of the electric shear strength

In this section, a physical model is proposed to link the electric shear strength to the electric charge onto surface skin generated by tape-stripping procedures.

#### 4.4.1. Physical model to estimate the electric charge, \( Q_s \), onto the stripped skin area

Human forearm can be considered as a dielectric material with dielectric constant \( _1 \). During the friction experience the forearm is fixed on a metallic support and it was assumed that only the tape-stripping (TS) area, \( S \), is electrically charged (\( S = 1.9 \times 2.5 \text{ cm} \)) (figure 7a). The fieldmeter device is above the forearm at a distance \( h \) equal to 1 mm. To estimate the electric charge, \( Q_s \), on the stripped skin surface, an electric physical model is suggested to modelize the experimental problem. The equivalent model consists in a plan capacitor with a
dielectric material inside and a dielectric constant, $\varepsilon_1$ (figure 7b). The thickness, $e_1$, of the dielectric material inside the plan capacitor, which symbolizes the human forearm, is chosen: $e_1 = 5 \text{ cm}$, which is the average thickness of the forearm of the volunteers in this study. The surface of the dielectric material is $S$, which corresponds to the surface of the tape-stripping area. The distance between the dielectric material and the fieldmeter device is noted, $h$, and equal to 1 mm as previously indicated. The environment between the dielectric material and the fieldmeter device is the air, which corresponds to the surface of the tape-stripping area.

Therefore, the potential difference can be written as a function of electric charge, $Q$, as

\[
V = \frac{Q}{S} \left( \frac{h}{\varepsilon_0} + \frac{e_1}{\varepsilon_1} \right).
\]

As a consequence the electric charge, $Q$, on the stripped skin surface is

\[
Q = \frac{e_0 VS}{(h + (e_1/\varepsilon_r(\text{skin})))},
\]

where $\varepsilon_r(\text{skin})$ is the skin relative permittivity given by $\varepsilon_1 = E_0 E_r(\text{skin})$.

The variation in the electric charge, $Q$, on the stripped skin, calculated with relation (4.9), for different values of relative skin dielectric constant, $\varepsilon_r(\text{skin})$, is shown in figure 8. The results are indicated for two values of voltage (4 kV and 5 kV) previously measured on stripped skin with a fieldmeter device (figure 5; filled square, $V = 5 \text{ kV}$; open square, $V = 4 \text{ kV}$).

The surface charge density, $\sigma$, is defined as $\sigma = Q/S$, therefore, the potential difference can be written as a function of electric charge, $Q$, as

\[
V = \sigma \left( \frac{h}{\varepsilon_0} + \frac{e_1}{\varepsilon_1} \right).
\]

The surface charge density, $\sigma$, is the skin relative permittivity given by $\varepsilon_1 = E_0 E_r(\text{skin})$.
By using the classical friction model, the classical frictional energy, $\Delta E_F$, between two surfaces in contact is the sum of two terms [33]:

$$\Delta E_F = \Delta E_{ad} + \Delta E_{load}. \quad (4.12)$$

where $\Delta E_{ad}$ is the van der Waals frictional adhesion energy and $\Delta E_{load}$ the frictional load energy due to the normal load applied.

By adding the electrical friction energy term in the previous classical frictional energy (4.12), the total frictional energy is written as

$$\Delta E_F = \Delta E_{ad} + \Delta E_{elec} + \Delta E_{load}. \quad (4.13)$$

By dividing the electrical friction energy by $d_0$, which corresponds to the lateral critical distance to initiate sliding, the friction force, $F_x$, is obtained:

$$F_x = \frac{\Delta E_F}{d_0} = \frac{\Delta E_{ad}}{d_0} + \frac{\Delta E_{elec}}{d_0} + \frac{\Delta E_{load}}{d_0}.$$

and

$$F_x = \frac{\Delta E_{ad}}{d_0} + \frac{1}{2} \frac{Q^2}{\varepsilon_0 S} \frac{d}{d_0} + \frac{\Delta E_{load}}{d_0}.$$

The new global adhesion component of the friction force is

$$F_{int} = \frac{\Delta E_{ad}}{d_0} + \frac{1}{2} \frac{Q^2}{\varepsilon_0 S} \frac{d}{d_0}. \quad (4.14)$$

By dividing relation (4.14) by the average contact area, $A$, which is the contact area between the spherical probe and the skin, the theoretical electric shear strength, linked to the electric charge on the skin
The parameters $d$ and $d_0$ are characteristics of the skin micro-relief. Therefore, the ratio $d/d_0$ is a roughness parameter, approximately equal to 1 for skin aged about 30 years.

The average contact area, $A$, between the spherical probe and the skin is calculated with the Hertzian theory: $A = \pi d^2$, where $d$ is the average penetration depth of the probe on the skin ($d \approx 1$ mm) and $R$ is the radius of curvature of the spherical probe. $R = 6.35$ mm [28]. The average contact area is around 20 mm$^2$.

Therefore, the theoretical electric shear strength calculated with equation (4.15) for both values of previously calculated $Q$ are reported in Table 1.

The comparison between the measured electric shear strength ($\tau_{\text{elec}} = 0.97$ kPa) and the theoretical values of the electric shear strength, obtained with the electrical physical model (Table 1), are in the same order of magnitude. The theoretical friction coefficient was calculated with equation (4.2), using the theoretical values of electric shear strength (Table 1) and reported in Figure 10. After tape stripping, the skin friction behaviour is highly modified (Figure 10). The electric charges generated by tape stripping add an electric component to the adhesive component of the friction force, which increases significantly the friction coefficient value (Figure 10). The proposed physical model seems to modelize the effect of the tape stripping on the skin friction behaviour. Integrating and defining an electric shear strength, $\tau_{\text{elec}}$, in the adhesive component of the friction force (4.1) or the friction coefficient (4.2).

5. CONCLUSION

It has been shown that the tape-stripping procedure generates electric charges on the skin surface, which greatly change the skin biotribological behaviour and modify the physico-chemical properties of the skin surface. It has been proposed to add to the friction adhesion component a term depending on the electric charge created by tape stripping, which is the electric shear strength, $\tau_{\text{elec}}$. The value of the electric shear strength has been experimentally estimated. A physical model has been proposed to theoretically estimate the value of the electric shear strength and to link the electric shear strength to the electric charge on the skin surface. Both values have been compared and they are in the same order of magnitude.

References


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