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Influence of epidermal hydration on the friction of human skin against textiles

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Friction and shear forces, as well as moisture between the human skin and textiles are critical factors in the formation of skin injuries such as blisters, abrasions and decubitus. This study investigated how epidermal hydration affects the friction between skin and textiles.

The friction between the inner forearm and a hospital fabric was measured in the natural skin condition and in different hydration states using a force plate. Eleven males and eleven females rubbed their forearm against the textile on the force plate using defined normal loads and friction movements. Skin hydration and viscoelasticity were assessed by corneometry and the suction chamber method, respectively.

In each individual, a highly positive linear correlation was found between skin moisture and friction coefficient (COF). No correlation was observed between moisture and elasticity, as well as between elasticity and friction. Skin viscoelasticity was comparable for women and men. The friction of female skin showed significantly higher moisture sensitivity. COFs increased typically by 43% (women) and 26% (men) when skin hydration varied between very dry and normally moist skin. The COFs between skin and completely wet fabric were more than twofold higher than the values for natural skin rubbed on a dry textile surface.

Increasing skin hydration seems to cause gender-specific changes in the mechanical properties and/or surface topography of human skin, leading to skin softening and increased real contact area and adhesion.

Keywords: biotribology; human skin; *in vivo* friction measurement; skin hydration; stratum corneum; textiles

1. INTRODUCTION

Human skin is practically in permanent contact with textiles during the various activities of everyday life when touching or wearing fabrics. Particularly, in bedridden persons, friction and moisture at the skin–textile interface are often associated with the feeling of discomfort (e.g. fabric sticking to the skin), or are even causes of mechanical skin irritations, trauma and wounds, such as decubitus (figure 1). Therefore, friction and shear, as well as moisture and liquids, are considered to be the major clinical criteria for assessing a person's risk of decubitus (Braden & Bergstrom 1987).

Sustained mechanical loading or pressure leading to tissue ischaemia have been widely acknowledged as the physical key factor in the pathogenesis of decubitus (Bader & Oomens 2006). Pressure and friction/shear in combination, as well as moisture, can, however, accelerate and promote skin decubitus formation (Bennett *et al.* 1979; Goossens *et al.* 1994). Friction and shear can lead to superficial skin abrasions as well as tissue deformation and distortion in deeper layers, thereby inducing altered stress distribution, impaired blood flow, oxygen and nutrient delivery, so that accumulation of waste products, cell death and finally tissue necrosis can occur (Goossens *et al.* 1994; Thompson 2005).

Elevated skin moisture levels (e.g. due to incontinence) macerate the skin, which can result in the loss of mechanical strength, greater susceptibility to skin injury or higher risk of infection (Faergemann *et al.* 1983; Mayrovitz & Sims 2001; Praessler & Fluhr 2005; Nakagami *et al.* 2006). It has been found that the presence of moisture/liquid on the skin (Elsner *et al.* 1990; Kenins 1994) or the therapeutic application of moisturizers (Ramalho *et al.* 2007), as well as stratum corneum (SC) damage caused by tape stripping (Pailler-Mattei *et al.* 2007) can greatly increase the frictional resistance of human skin.

On the other hand, moisture (i.e. water) plays a crucial role in the homeostasis of the SC and the physiology of the human skin (Praessler & Fluhr 2005). Water maintains the metabolism, enzyme activity,

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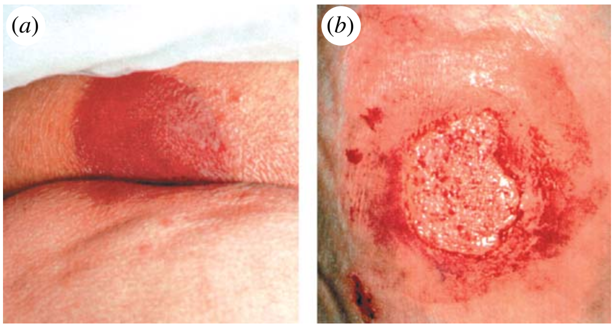

Figure 1. Two initial decubitus ulcers according to the classification of the European Pressure Ulcer Advisory Panel (Dealey & Lindholm 2006). (*a*) Grade 1: non-blanchable erythema of intact skin and (*b*) grade 2: partial thickness skin loss involving epidermis and/or dermis. The ulcer is superficial and presents clinically as an abrasion, blister or shallow crater (with permission and by courtesy of PAUL HARTMANN AG, Heidenheim, Germany).

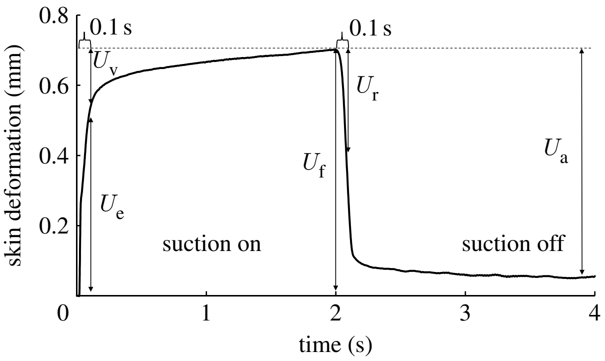

Figure 2. Typical viscoelastic behaviour of human skin as a response to a cutometer suction–relaxation cycle (stress time mode). The deformation of the skin on the volar forearm is plotted as a function of time. Following the nomenclature of Agache *et al.* (1980), the parameters used to describe the deformation and the viscoelastic properties of skin are immediate elastic distension (U_e), delayed distension or viscoelastic creep (U_v), total skin extensibility or deformation (U_f), as well as immediate (U_r) and final (U_a) retraction after removal of the vacuum.

structure and barrier function of the SC (Edwards & Marks 2005). Water imparts suppleness, elasticity, plasticity, flexibility and softness to the skin (Barel & Clarys 2006).

Tribology is defined as the ‘study of friction, wear and lubrication, and the science and technology of interacting surfaces in relative motion’ (Jost 1966). Biotribology in particular encompasses tribological aspects related to biological systems (Dowson & Wright 1973), such as the lubrication of natural/artificial joints. Sivamani *et al.* (2003*a*) have reviewed the current research on skin biotribology, dominated by dermatological studies concerning the effects of cosmetics. Most of the *in vivo* skin friction studies were fundamental and conducted using solids (e.g. steel, polymers, glass) as rubbing partners. In the past, fabric friction was primarily instrumentally determined without considering appropriate mechanical skin equivalents (Derler *et al.* 2007). A polyurethane-coated polyamide fleece with a surface structure similar to that of human skin has recently been shown to simulate

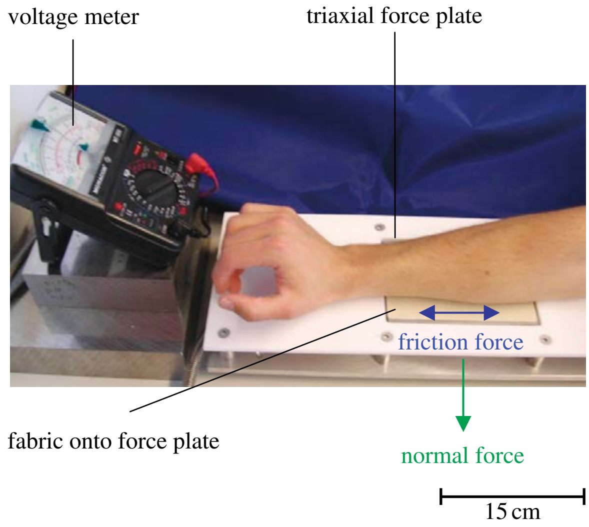

Figure 3. *In vivo* skin–fabric friction experiments on a force plate. The skin frictional resistance is determined by rubbing the volar forearm in a reciprocating motion against the textile on the force plate. Normal load is controlled by checking needle deflection of a voltage meter.

human skin under dry sliding conditions when objectively assessing the frictional behaviour of fabrics using a textile friction measurement device (Derler *et al.* 2007; Gerhardt *et al.* 2008).

Several studies have demonstrated that the friction coefficient (COF) of textile materials against skin or other fabrics is mainly influenced by the nature of the fabric (i.e. fibre materials, textile structure), contact pressure, sliding velocity, as well as ambient humidity and skin moisture content (Comaish & Bottoms 1971; Elsner *et al.* 1990; Johnson *et al.* 1993; Kenins 1994; Zhang & Mak 1999; Ramkumar *et al.* 2004; Derler *et al.* 2007; Gerhardt *et al.* 2008). *In vivo* skin–fabric friction has not yet been studied in detail, and the role of textiles in the formation and prevention of decubitus is largely unexplored (Zhong *et al.* 2006). In the past, fibre-based materials on the skin were mainly investigated in terms of comfort, sensation, grip (fabric hand), thermophysiological as well as tactile properties (Verrillo *et al.* 1998; Hatch & Maibach 2004; Bertaux *et al.* 2007).

Moisture commonly increases the friction at the skin–textile interface, as is experienced in everyday life, e.g. in sport activities. For skin friction, factors of 1.5–7 have been reported between wet and dry conditions (Comaish & Bottoms 1971; Highley *et al.* 1977; Wolfram 1983; Johnson *et al.* 1993; Kenins 1994; Adams *et al.* 2007). So far, however, no systematic study on the functional relationship between skin moisture and textile friction has been presented, even though a few investigations have been performed to compare different hydration levels with *in vivo* skin friction (El-Shimi 1977; Elsner *et al.* 1990; Lodén *et al.* 1992; Sivamani *et al.* 2003*c*). Lodén *et al.* (1992) determined skin friction against an oscillating steel plate and found significant correlations between moisture and friction for the lower back in atopic and normal skin.

The objective of this study was to investigate in detail the impact of epidermal hydration on the friction

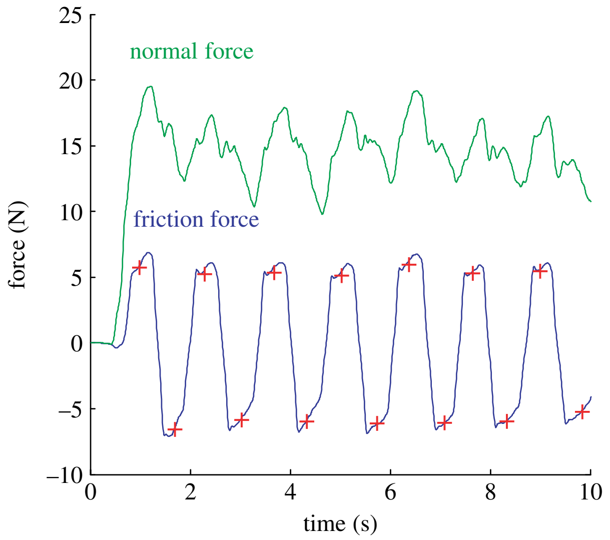

Figure 4. Typical friction and normal force traces from *in vivo* skin friction experiments on the force plate. The reciprocating motion between forearm and textile induces compressive and tensile forces to the quartz force plate, which are reflected in bipolar friction force signals. The error crosses denote the variation in the friction force and the time window, in which mean friction forces and the corresponding normal loads were calculated for determining friction coefficients (equation (2.1)).

against fabrics. Skin hydration and elasticity measurements were combined with friction experiments on a force plate to link the physiological skin condition to skin–textile friction. Stepwise increases in skin hydration were induced by iterative immersion into isotonic saline solution.

2. MATERIAL AND METHODS

2.1. Study participants

Twenty-two healthy Caucasians were recruited from our institute. All persons (11 males, 11 pre-menopausal females; age: 31.7±8.4 years; BMI: 23.3±3.2 kg m^{-2}) participated voluntarily and signed informed consent for the study purpose. Exclusion criteria of the study were non-intact skin conditions, any history of skin disease, allergies and tobacco abuse (more than 15 cigarettes per day).

2.2. Skin analysis

All experiments were conducted at 23±1°C and 50±2% relative humidity after an acclimatization period of 15 min. The examined skin region was the dominant inner forearm, an easily accessible, sun-protected and mostly hairless skin region. The subjects were asked not to apply cosmetics (e.g. creams, lotions) on the test site for at least 2 days before the measurements, and not to shower and to do sports 6 hours before skin testing. Excessive hairs, casually present at the forearm of males, were gently removed using scissors, razor blades or depilatory cream approximately 3 days in advance. All tests were performed by one investigator (L.-C.G.) in order to standardize the experimental procedure and minimize the measurement uncertainty.

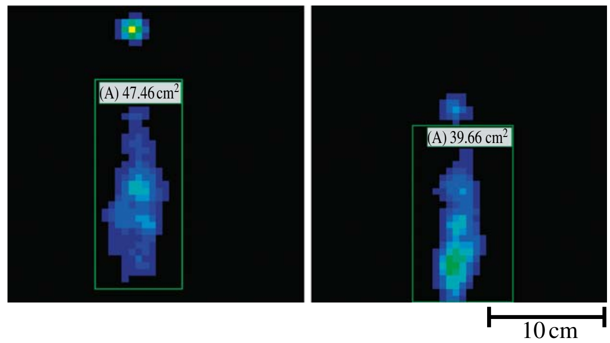

Figure 5. Determination of the apparent contact area between the inner forearm and the force plate using a pressure-sensitive film. The local pressure distribution and the contact area represented by the number of loaded sensor elements are shown for two subjects. The thenar eminence lay outside of the measuring field and was excluded from the calculation.

Skin hydration was assessed at approximately 15 locations on the inner forearm using a corneometer probe (CM 825; Courage & Khazaka, Cologne, Germany) that measures the epidermal moisture content by penetrating the skin up to a depth of 10–20 μm, representing the normal thickness of the SC (Khazaka 2005). The corneometer method uses the high dielectric constant of water ($\varepsilon_r = 81$) for detecting the water-related changes in the electrical capacitance of the skin. Corneometer measurements are given in arbitrary units and were recently related to physiological skin types. CM values below 30 characterize very dry, between 30 and 40 dry and greater than 40 normally moist skin (Heinrich *et al.* 2003).

The mechanical properties of the skin were measured using a 4 mm diameter aperture suction device (Cutometer MPA 580; Courage & Khazaka, Cologne, Germany). The cutometer applies negative air pressure to the skin surface, by which the skin is drawn upwards into the probe opening. The amplitude of the resulting skin deformation is measured as a function of time (figure 2) by an optical system (Berndt & Elsner 2002).

Cutometer measurements were performed on a single previously marked forearm location. A constant vacuum of 450 mbar was applied to the skin for 2 s, followed by a relaxation time of 2 s (figure 2). The cutometer-specific R values, adapted from Agache *et al.* (1980), were analysed. Besides the total skin deformation ($R_0 = U_f$), the overall elasticity, including creep–creep recovery ($R_2 = U_a/U_f$), the pure elasticity, ignoring viscoelastic creep ($R_5 = U_r/U_e$), the ratio of viscoelastic to elastic extension ($R_6 = U_v/U_e$), as well as the biological elasticity ($R_7 = U_r/U_f$), i.e. the ratio of elastic recovery to total deformation, were determined from the first suction–relaxation cycle (figure 2). The relative parameters R_2, R_5, R_6 and R_7 do not depend on skin thickness, and can therefore be compared between different sampling sessions, anatomical sites and subjects (Berndt & Elsner 2002).

2.3. Determination of the apparent contact area

Prior to all moisturization–friction experiments, the apparent contact area between the skin and the force plate was determined using a pressure-sensitive film (model 5250; Tekscan, Boston, MA, USA; sensor density: 3.2 elements cm^{-2}). The test subjects were asked to press with a force of 15 N (checked by needle deflection of an analogue voltage meter; figure 3) against the force plate covered with the film. Under this loading condition, the apparent contact area of the volar forearm was determined at the height of the wrist knuckle (ulnar styloid process) towards the elbow by calculating the number of loaded sensor elements. The applied loading conditions and the person's underlying forearm geometry/anatomy resulted in apparent contact pressures that are clinically relevant for supine persons (see §3.1).

2.4. In vivo *skin friction measurements*

Friction measurements were carried out using a triaxial quartz force plate (model 9254; Kistler, Winterthur, Switzerland), as recently described (Derler *et al.* 2007). All textiles were preconditioned for 12 hours under laboratory conditions. Prior to the test, fabric swatches (10×15 cm) were stuck to the force plate using a double-sided adhesive tape (figure 3).

The volunteers were instructed to rub their dominant inner forearm in a reciprocating and uniform motion (approx. 20 cycles) against the textile on the force plate, using normal loads of 14.8 ± 1.3 N. The friction process (frequency: 0.9 ± 0.2 Hz; estimated forearm stroke: approx. 80 mm) was carried out with a linear sliding velocity of approximately 140 mm s^{-1}, which occurs clinically when carefully repositioning or gently moving a person during a bed transfer. Such a velocity was verified and obtained by pretests, in which the duration and displacement of passive body movements on a hospital mattress were monitored and evaluated by video sequences. Sliding velocities varied between 95 and 225 mm s^{-1}.

DYNOWARE software (type 2825A-02, v. 2.4.1.5; Kistler, Winterthur, Switzerland) was used to acquire the friction and vertical force (sampling rate: 125 Hz; friction and normal force resolution: approx. 1 mN) and correct drifts in the raw data. The force signals were analysed and the COFs were calculated with a home-made MATLAB software code (v. 7.0.4; The MathWorks, Inc., Natick, MA, USA). The dynamic COF was calculated from the centres of the friction force plateaus (averaged over approx. 11 data points, indicated by error crosses) and the respective vertical forces (figure 4). The average dynamic skin COF obtained from at least 15 full friction cycles (i.e. the mean of 30 or more consecutive friction-to-normal force ratios) was determined according to

$$\bar{\mu}_{\text{dynamic}} = \frac{1}{n}\sum_{i=1}^{n}\frac{\bar{F}_{\text{friction},i}}{\bar{F}_{\text{normal},i}}, \qquad n \geq 30. \qquad (2.1)$$

2.5. Generation of different skin hydration states

In order to systematically create different skin hydration conditions, the skin of the subjects was exposed to isotonic sodium chloride solution (0.9% w/v NaCl, 154 mM) using a water bath (volume: 25 l; Thermostat RM25; Lauda-Königshofen, Germany) that maintained a temperature of 35 ± 0.5°C. Non-sterile isotonic solution was prepared with deionized water. After the baseline measurements, i.e. skin analysis and friction experiment in the natural skin condition, the skin was iteratively soaked in NaCl solution (pH 6) for 5, 10 and 15 min. After each immersion period, visible excess water at the inner forearm was gently wiped away with a non-woven soft tissue. Subsequently, cutometer and corneometer measurements were performed within 2 min, followed by the friction test on the force plate. In order to simulate extreme moisture/liquid accumulation on the skin surface (e.g. heavily/abnormally sweating or incontinence), the hospital fabric was completely soaked with NaCl solution (approx. 10 µl cm^{-2}) by means of a syringe.

2.6. Fabric samples

To ensure clinical relevance, a commercially available medical textile (Art. 142004; Leinenweberei Bern, Switzerland) was specified for the friction experiments. The hospital fabric, a plain weave (1/1) made of intermingled cotton (50%) and polyester (50%) weft and warp yarns, had no chemical finishing or coloration. For each subject, the same fabric sample was employed throughout a cycle of moisturization–friction experiments, and was exchanged for each new test person. In the friction experiments, the inner forearm was rubbed along the weft direction of the textile.

2.7. Statistical analysis

Statistical analyses were performed using SPSS v. 14.0.1 (SPSS, Inc., Chicago, IL, USA). Since the data from all measurements showed neither normal distribution nor variance homogeneity even after transformations, distribution-free rank tests were chosen. For all analyses, statistical significance was set at a probability value of $p < 0.05$. All results are expressed as mean ± 1 s.d., or alternatively as a median, describing the typical value obtained from skewed experimental data.

Depending on the person, maximum skin hydration (MSH) associated with maximum friction was achieved after the second or third soaking period. To assess gender-specific differences in moisture-related skin–fabric friction, the percentage of change in friction and moisture content at MSH in relation to the baseline were analysed using a two-tailed unpaired Mann–Whitney *U*-test. Possible gender differences in the apparent contact area, as well as in the percentage of change of the viscoelastic skin properties were assessed by two-tailed rank-sum tests (*U*-tests).

3. RESULTS

3.1. Contact area measurements

Apparent contact areas in the natural skin condition between the medium volar forearm and the force plate ranged from 36.3 to 56.5 cm^2 (mean: 44.0 ± 5.4 cm^2; figure 5), without any significant difference for men and women ($p=0.519$). Considering the respective normal forces during the rubbing process (approx. 15 N), the average apparent contact pressures were 3.4 ± 0.5 kPa, which is close to the maximum interface pressures observed for supine persons (Defloor 2000; Gerhardt *et al.* 2008).

3.2. Friction experiments

A highly positive linear relationship between moisture and friction was found in all 22 persons, with coefficients of determination $R^2 > 0.72$ ($p < 0.05$), obtained from linear curve fitting (figure 6). This means that for each individual at least 72% of the variability of the COF can be explained by the systematic influence of the moisture content. Coefficients of determination found for quadratic or exponential functions were of the same order of magnitude. Figure 6 shows typical cases for two male and two female subjects. The baseline COFs of 0.41 ± 0.04 (men) and 0.42 ± 0.03 (women) rose to 0.56 ± 0.06 (men) and 0.66 ± 0.11 (women), respectively, as a consequence of three iterative soaking cycles. In the natural skin condition, there was no significant difference ($p=0.30$) in the epidermal moisture CM between men (32.6 ± 4.4) and women (29.9 ± 4.0). Figure 7 shows the time-dependent evolution of the skin moisture during the moisturization–friction experiments.

At MSH, skin–fabric friction was typically 51% (median, mean: 56 ± 27%) higher in women and 37% higher (median, mean: 36 ± 7%) in men, while skin hydration increased by approximately 45% (median, mean: ♂ 46 ± 13%, ♀ 45 ± 12%) compared with the baseline moisture content (figure 8). There was no statistically significant difference in the increase in skin moisture between men and women ($p=0.797$). However, the increase in friction was significantly higher ($p=0.016$) for women. With a very similar increase (approx. 45%) in skin moisture compared with the natural skin condition, female skin showed approximately 20% greater frictional resistance, i.e. the skin of women reacted more sensitively to moisture-induced changes (figure 8).

By assigning all measured COFs to physiological skin conditions, median COFs varied between 0.42 on very dry skin (men and women) and 0.53 (men) and 0.61 (women), respectively, on normally moist skin. There is a gradual increase in the COF from very dry to normal skin (figure 9). The COF increased typically by 26% in men and 43% in women, indicating greater susceptibility of females to moisture-induced changes in skin–textile friction ($p < 0.001$, for normally moist skin; figure 9).

A factor of more than 2 was found between the friction of skin in the natural condition and the measurement against the wetted fabric (figure 10), with COFs of 0.88 ± 0.08 for men and 0.95 ± 0.04 for women being significantly different from each other ($p=0.047$).

None of the measured viscoelastic skin properties correlated with skin moisture or fabric friction. Focusing on the changes between MSH and baseline, cutometer measurements revealed no significant differences between men and women in the viscoelastic parameters (table 1). Variations in R_0 and R_2 were marginal and amounted to a few per cent for both men and women. It should be, however, pointed out that in both genders, the viscosity R_6 slightly decreased, whereas the pure elasticity R_5 and the biological elasticity R_7 increased table 1 as a consequence of the repetitive immersion bath.

4. DISCUSSION

4.1. Friction experiments

We found a linear relationship between skin moisture and skin–fabric friction in each individual tested. Such a linear behaviour was not expected because nonlinear material behaviour is typical for living tissues in general and soft tissues in particular (Fung 1993). Human skin is characterized by nonlinear viscoelastic, anisotropic, quasi-incompressible mechanical properties (Jachowicz *et al.* 2007; Kabla & Mahadevan 2007; Delalleau *et al.* in press) that are often associated with those of a soft elastomer (Adams *et al.* 2007). The concepts of the friction theory for elastomers (Moore 1972) imply a two-term friction model consisting of an adhesion (surface effect) as well as a deformation (bulk phenomenon) component and have been adopted to human skin (Dowson 1997). For skin, the main contribution to the friction is considered to be adhesion, whereas deformation mechanisms are normally unimportant (Wolfram 1983; Johnson *et al.* 1993; Adams *et al.* 2007).

Remarkably, the friction of female skin was more susceptible to moisture (figures 6 and 8–10). Possible explanations can be gender-specific changes in the anisotropic mechanical properties of the SC and the underlying tissue, increased adhesion due to enhanced skin softening or altered skin surface topography in women (e.g. formation of a greater true contact area) upon the iterative soaking procedure. Greater epidermal and dermal thickness (Seidenari *et al.* 1994; Eisenbeiss *et al.* 1998), greater corneocyte surface area (Fluhr *et al.* 2001), as well as lower surface roughness R_a and higher furrow density of forearm skin (Lagarde *et al.* 2005) have been reported for pre-menopausal women compared with men in the same age group. Until now, no significant gender differences have been reported for skin friction (Cua *et al.* 1990, 1995; Kenins 1994; Sivamani *et al.* 2003*c*). Kenins (1994) found no difference between men and women in the friction of textiles against dry and moist skin (fingers, hairy forearm skin). Different skin regions, conditions and test methods might explain the deviation from our results.

The female test persons generally showed larger variations in skin–fabric friction and moisture uptake than men (figure 8). We attribute these variations to the menstrual cycle that is normally associated with changes in sex hormone levels (e.g. oestrogen), as well as in the water balance (Berardesca *et al.* 1989; Eisenbeiss *et al.* 1998). In the pre-menstrual phase, for example, the human body retains large amounts of salts and water. This fluid retention in deeper tissue layers (e.g. dermis) probably decreases skin extensibility and might cause higher skin tension as well as flattening

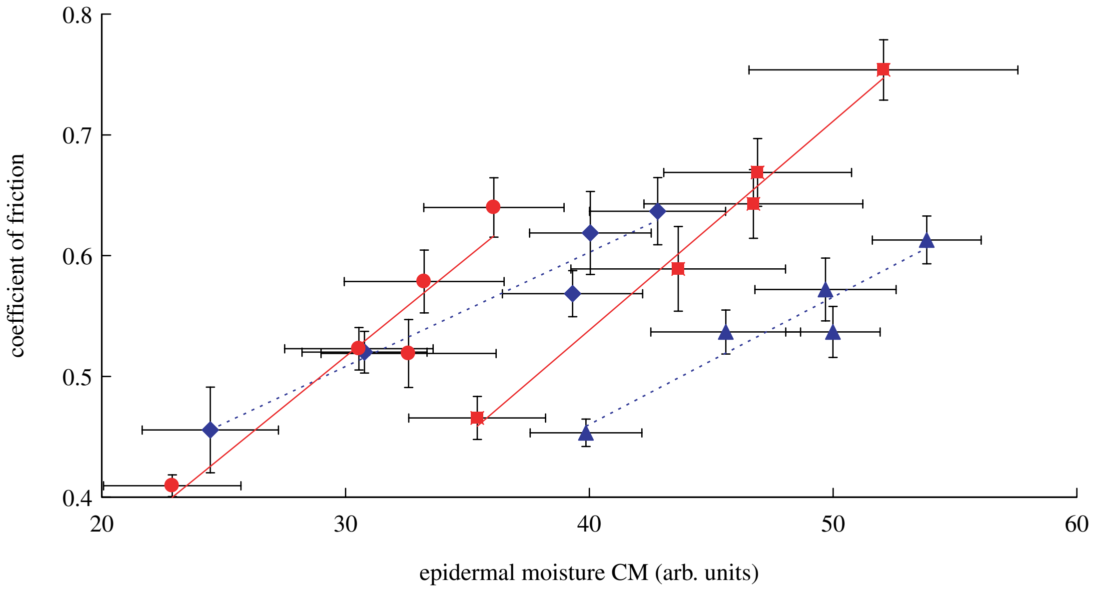

Figure 6. Effect of epidermal moisture on the friction of skin against a hospital textile. A high linear correlation between skin hydration and friction coefficient was found for all persons. The influence of moisture on the textile friction was more prominent in women, as indicated by greater slopes obtained from linear fits. For clarity, four typical cases are shown. Subsequent to the 2 min measuring interval of the third immersion, an additional corneometer and friction measurement was performed after a drying time of 2 min at laboratory conditions, explaining five data points in the graph. Diamonds, subject 1 (male); triangles, subject 2 (male); circles, subject 3 (female); squares, subject 4 (female).

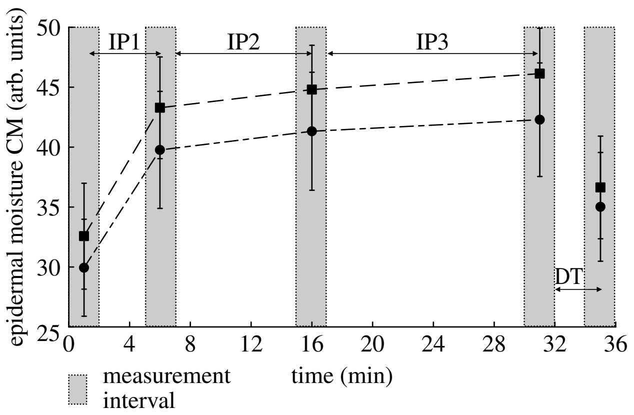

Figure 7. Skin moisture content as a function of soaking time into isotonic saline solution. The graph demonstrates the means ±1 s.d. for men and women, obtained by corneometry. There is a gradual increase in skin moisture during the three immersion periods. A strong water uptake occurs within the first immersion period (IP1), followed by slow increases in epidermal moisture during IP2 and IP3. The skin seems to become saturated as a consequence of the prolonged soaking procedure. Subsequent to the 2 min measurement interval of IP3, the skin was allowed to recover and dry at laboratory conditions for another 2 min (DT). Skin moisture dropped by 70% (men) and 59% (women) from the maximum value, indicating fast water evaporation and re-establishment of the natural skin condition. Squares, men; circles, women.

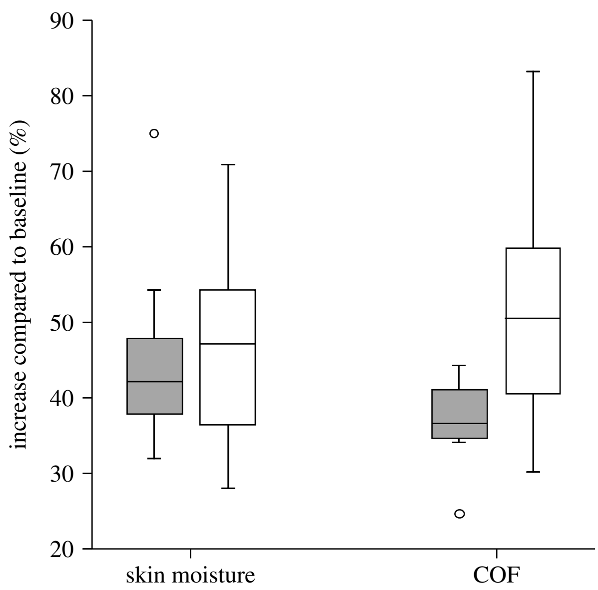

Figure 8. Gender-dependent increase in skin moisture content and friction at MSH compared with the natural skin condition. Boxplots for men and women are shown. The box contains the central 50% of the ordered data and stretches between the lower and upper quartile, representing the interquartile range (IQR). The horizontal bar within the box denotes the median. The whiskers indicate the minimum and maximum, or the largest and smallest values that are not outliers. Outliers, i.e. cases/COFs with values greater than 1.5 IQRs (box lengths) from the quartiles, are labelled as open circles. Moisture increased in both genders similarly by approximately 45% ($p=0.797$). The increase in friction was more distinctive in women and significantly different for the two genders ($p=0.016$). Filled boxes, male; open boxes, female.

of small wrinkles in the skin surface micro-relief (Berardesca *et al.* 1989). Smoother skin probably increases the real contact area (RCA) and adhesion to a fabric.

To our knowledge, the relationship between moisture-related skin types (very dry, dry, normally moist) and fabric friction has not been studied in detail and reported before. Using corneometry in combination with friction experiments on the force plate, we showed that COFs of skin against a hospital textile increased from very dry to normally moist skin by 33% (median of all 22 persons; figure 9).

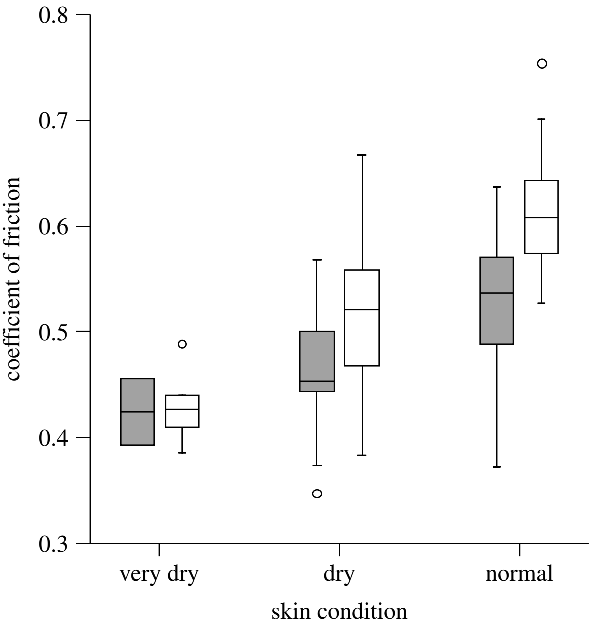

Figure 9. *In vivo* skin–fabric friction with regard to moisture-related skin types (Heinrich *et al.* 2003). A gradual increase in friction from very dry to normal skin can be discerned for both genders. Male: very dry, $n=2$; dry, $n=19$; normal, $n=34$. Female: very dry, $n=6$; dry, $n=27$; normal, $n=22$. The skin of women shows greater moisture sensitivity. Filled boxes, male; open boxes, female. Open circles denote outliers, i.e. COFs with values greater than 1.5 box lengths from the quartiles.

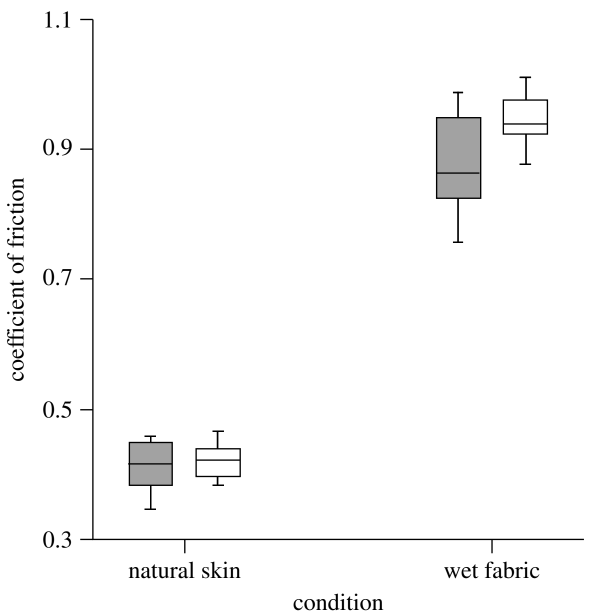

Figure 10. Friction of skin in the natural and wet condition. On the wet fabric, the friction was more than twofold higher in both men and women ($p=0.974$). A statistically significant difference between both genders was found for the friction against the wet fabric ($p=0.047$), confirming the greater moisture sensitivity of female skin. Filled boxes, male; open boxes, female.

This result is in good accordance with early measurements by Comaish & Bottoms (1971), as well as by Nacht *et al.* (1981), who found increases in friction between 20% for wool and 60% for polytetrafluoroethylene upon skin moisturization, respectively. In

Table 1. Percentage of change (mean ± 1 s.d.) in all cutometer parameters at the MSH compared with the natural skin condition. No gender-specific differences were found for the measured cutometer parameters.

	percentage of change		
parameter	male ♂	female ♀	p value (♂ versus ♀)
R_0	0.7±13.6	1.4±9.3	0.699
R_2	1.8±5.0	0.3±3.6	0.748
R_5	5.5±8.4	3.3±9.5	0.562
R_6	−4.9±11.9	−5.2±11.4	0.898
R_7	6.9±8.3	4.8±10.6	0.606

general, factors between 1.5 and 7 have been reported in the literature for skin COFs before and after immersion into water or treatment with moisturizing formulations (Comaish & Bottoms 1971; Highley *et al.* 1977; Wolfram 1983; Johnson *et al.* 1993; Kenins 1994; Adams *et al.* 2007). This large spread probably derives from the diversity of test methods, materials and experimental parameters used. One of the most important factors is probably the time delay between a friction measurement and moisturizer application or water exposure of the skin.

The average COFs of skin against a completely wet cotton–polyester fabric ($\mu=0.91$) exceeded those in the natural skin condition ($\mu=0.42$) by a factor of more than 2 (figure 10). Our measurements confirm the results of Kenins (1994) who observed a factor of approximately 2 in friction when rubbing dry and wet cotton–polyester fabrics against the skin. Our baseline values were close to skin–fabric COFs reported in the literature. Comaish & Bottoms (1971) measured on the back of the hand a dynamic COF of 0.40 for wool knitwear. Zhang & Mak (1999) obtained dynamic COFs between 0.49 and 0.52, when rubbing cotton knitted fabrics against forearm skin.

Owing to the viscoelastic material properties, the tribology of human skin is primarily influenced by the pressure, the type and velocity of relative motion, the physical nature of contacting materials and the physiological skin condition (Comaish & Bottoms 1971; Johnson *et al.* 1993; Sivamani *et al.* 2003*a*; Adams *et al.* 2007; Derler *et al.* 2007). Therefore, friction experiments have to be carried out with defined and case-specific parameters. For decubitus prevention, particularly, the apparent contact pressure (normal load) and the sliding speed (friction frequency) are important to be specified. There were no significant differences (U-test) between men and women in all test parameters (including friction frequency, apparent contact area, contact pressure), allowing the COFs to be reliably compared between the genders.

In this investigation, no significant correlation was found between epidermal moisture and skin viscoelasticity on the one hand, and between viscoelasticity and skin–textile friction on the other hand. For both genders, the iterative immersion procedure had only a slight effect on the viscoelastic skin properties (table 1). Our observations are in line with other studies (Murray & Wickett 1997; Dobrev 2000), in which no significant correlations between skin hydration measurements and mechanical parameters were found.

The lack of sensitivity to hydration suggests that the underlying tissue is dominating the response of the suction device. Skin elasticity measurements are normally influenced by the chosen cutometer parameters (Agache & Varchon 2004). In our case (probe aperture: 4 mm; vacuum: 450 mbar), deeper skin layers might have been aspirated, thereby characterizing epidermal and dermal mechanical properties together and therefore being insensitive for detecting the moisture-induced changes in the elastic properties of the SC, which is assumed to determine the tribology of human skin (Johnson *et al.* 1993; Adams *et al.* 2007; Pailler-Mattei *et al.* 2007).

4.2. Role of the SC and water in skin tribomechanics

A very recent study of Pailler-Mattei *et al.* (2007) suggests that the lateral stiffness of the SC might be the key mechanical property for skin friction. The SC on the volar forearm is very thin (approx. 17 μm; Agache 2004) and represents only 1/100 to 1/50 of the total skin thickness, but its stiffness (dry SC: 120–1000 MPa; wet SC: 26–100 MPa) is at least two orders of magnitude higher than that of the underlying subcutaneous tissue (Agache 2004; Yuan & Verma 2006; Pailler-Mattei *et al.* 2007). Therefore, the role of the SC in the mechanical properties of the whole skin is often overlooked and underestimated (Barel 2002).

According to Pailler-Mattei *et al.* (2007), the SC does not influence the skin bulk mechanical properties, but it does influence the tangential mechanical response of the skin. They found that in more hydrated SC layers the decrease in lateral stiffness was more prominent than the decrease in normal stiffness. This finding can explain our observation that perpendicularly measured skin viscoelasticity did not significantly correlate with skin–fabric friction and skin hydration. Likewise, our cutometer measurements could also reflect that epidermal moisture uptake might have altered and modified the skin surface topography rather than the viscoelastic skin properties on the volar forearm.

The physical effects of water leading to increased skin frictional resistance have been extensively and controversially debated. Adhesion has been proposed as the main cause of skin friction, assuming that COFs increase with decreasing load and as modulus decreases, e.g. when skin is plasticized due to water exposure or moisturization (Wolfram 1983; Koudine *et al.* 2000; Sivamani *et al.* 2003*b*; Pailler-Mattei *et al.* 2007). It is interesting to note that removal of the SC by tape stripping increased skin adhesion forces as well as COFs twofold (Pailler-Mattei *et al.* 2007). According to the literature (Yuan & Verma 2006; Pailler-Mattei *et al.* 2007), water reduces the elastic modulus of the SC by a factor of between 2 and 10, allowing one to reasonably argue that the water-related increase in skin frictional resistance is due to greater compliance of surface asperities and hence increase in the RCA and adhesion.

Moisture uptake of the skin is believed to induce skin softening, smoothing and reduction in interfacial shear strength. Skin friction commonly increases upon moisture exposure, implying that increase in RCA dominates the interfacial shear strength reduction (Adams *et al.* 2007). The large increase in friction in the presence of water is apparently a result of the moisture-dependent mechanical properties of the SC (Johnson *et al.* 1993). We attribute the large increase in friction to the plasticizing effect of water, leading to a greater RCA. We believe that capillary bridges (fluid menisci) formed by superficial water micro-droplets play an unimportant role for the increase in RCA.

4.3. Skin water balance and chemistry of SC hydration

We noted that the skin occasionally became saturated with water, even after the second immersion cycle, i.e. showed a similar or even slightly decreased moisture content after the third soaking. This observation suggests that human skin might possess physiological regulatory processes or important mechanisms preventing the SC/epidermis from extreme overhydration and tissue breakdown. However, the exact physicochemical mechanisms of skin moisturization are not yet fully understood (Larsen & Jemec 2005), and little is known about the interfacial phenomena and biophysics of skin hydration, i.e. water uptake or imbibition of water into the epidermis.

An essential mechanism of maintaining water balance in the SC is through the so-called natural moisturizing factors (NMFs). The NMFs are hygroscopic, water-soluble, osmotically active molecules consisting of free amino acids (40%), pyrrolidone carboxylic acid (12%), lactate (12%), sugars (approx. 9%), urea (7%) and inorganic ions (20%; Rawlings & Harding 2004). The production of NMFs takes place in the granular layer of the SC and is regulated by skin moisture or ambient condition. NMF generation will be suppressed or even inhibited if skin is sufficiently moisturized or xerotic (Harding 2004; Rawlings & Harding 2004; Fluhr *et al.* 2005).

In healthy persons, NMF concentration as well as moisture content decline towards the surface of the skin (Rawlings & Harding 2004). Highly structured lipid lamellae as well as restricted water movement through the SC effectively prevent the water-soluble NMF compounds from leaching out of the corneocytes in the surface layers of the skin (Harding 2004).

There is experimental evidence (Middleton 1968, 1969; Van der Pol *et al.* 2005*a*,*b*) for our assumption that two competitive effects play an important role in the moisturization of human skin: first, water uptake and binding to NMFs, and second, reduction or leaching out and removal of specific surface-active NMF molecules due to epidermal lipid barrier damage or permeability perturbation. The latter effects probably decrease the SC water-binding capacity and increase water evaporation, which in turn can induce the formation of dry skin.

Van der Pol *et al.* (2005*a*,*b*) using micro-Raman spectroscopy (resolution: 5 μm) observed a washout of urea and lactate, as well as of ceramides and cholesterol in the most superficial SC upon immersion in tap water (36°C, 30 min). Unexpectedly, they found an increase in NMF amino acids, from which they hypothesized that the temperature conditions might have been favourable for NMF generation, thereby stabilizing the NMF levels and re-establishing the moisture levels in the SC as a long-term regulation effect.

According to Middleton (1968, 1969), the SC takes up and loses water by osmosis. He proposed that a semipermeable membrane system impedes the NMFs from leaving the corneocytes upon immersion into water. However, following long-lasting soaking, the cell membranes increase their permeability so that the NMFs can escape. This conclusion has not been contradicted to date, and it supports our observation (figure 7) that, upon prolonged bathing, skin becomes saturated with water at a certain time point, from which it loses moisture content and starts to become dry.

4.4. Water and the SC: skin wrinkling, morphology and molecular changes

From a physiological view, human skin acts as a water barrier and keeps water in and out of the human body. When brought in contact with aqueous solutions, the keratin-filled corneocytes immediately imbibe and absorb the water. Water first seeps into the spaces between the flakes of the dead SC. Subsequently, the dead corneocytes become rehydrated, swell and expand, thereby increasing their surface area. As the SC is firmly attached to the underlying epidermal and dermal skin layers, the SC must wrinkle (e.g. as seen in 'prune fingers') in order to compensate for the greater surface area. The SC on the fingers, palms and soles is relatively thick (0.5–1 mm; Agache 2004), i.e. holds more keratin, and is, thus, able to absorb and imbibe more water, which makes the wrinkling more evident. Owing to its small thickness (approx. 17 μm; Agache 2004), the SC at the volar forearm cannot pull effectively against its connection with the dermis, explaining that macroscopically no skin wrinkling was observed by thorough visual inspection after immersion.

Morphological and structural changes of the SC due to water uptake or water exposure are well documented in the literature (Querleux *et al.* 1994; Rawlings *et al.* 1995; Van Hal *et al.* 1996; Norlén *et al.* 1997; Warner *et al.* 1999, 2003; Sato *et al.* 2000; Bouwstra *et al.* 2003; Richter *et al.* 2004). For example, a twofold reduction in the skin surface roughness (Sato *et al.* 2000), as well as SC swelling of approximately 8% in the area dimension and 26% in the thickness dimension, has been observed under water treatment (Norlén *et al.* 1997). Prolonged exposure to water leads to thickening of the SC resulting from corneocyte swelling (threefold after 4 hours, fourfold after 24 hours) and the storage of water-soluble substances in intercellular cisternae (Van Hal *et al.* 1996; Warner *et al.* 2003). These water-related changes in the SC present a dynamic dimension of the brick-and-mortar model (Elias 1983), being able to adapt to external stress factors such as overhydration (Praessler & Fluhr 2005).

Water is the plasticizer of keratin, allowing the SC layer to bend and stretch, avoiding cracking and fissuring. In the SC, water can be found in three types or chemical bonding states: primary water, which is tightly bound to keratin in corneocytes; secondary water, which is hydrogen-bonded around the protein-bound water; and free/bulk water (Rawlings & Harding 2004; Lévêque 2005). At normal physiological conditions, the SC water mainly exists in a bound state (Lévêque 2005), and the high osmotic strength within corneocytes allows them to soak in water, which prevents the accumulation of water between corneocytes (Wertz & Michniak 2005). When it is totally hydrated, however, extracellular water pools or voids do occur that can disrupt the SC structure and even shift lamellar bilayers, creating amorphous intercellular zones (Warner *et al.* 1999, 2003). These modifications are reversible (Van Hal *et al.* 1996). Hyperhydration of the skin by a long bath causes the SC surface to be easily rubbed off due to progressive degradation of corneo-desmosomes and disruption of intercellular bilayer lipids (Van Hal *et al.* 1996; Bouwstra *et al.* 2003; Warner *et al.* 2003; Lodén 2005). Such morphological changes also have been described in the literature as being a consequence of mechanical stress upon large SC extensions (Rawlings *et al.* 1995).

4.5. Study limitations

We would like to note here that macroscopically invisible surface alterations, SC damage due to the repetitive rubbing process as well as the formation of invisible hair stubble or pits due to casual shaving cannot be completely ruled out. However, we believe that these changes had a negligible influence on the measurements because there was no difference in skin friction between men and women in the natural skin condition. A limitation of our study was that only a single skin location was measured with the cutometer probe to maintain stable test and skin conditions, i.e. minimizing water evaporation or skin recovery. It is furthermore known that the dielectric properties of NaCl ($\varepsilon_r = 5.9$) can affect the electrical capacitance. However, the influence of salt on corneometer measurements has been reported to be unimportant (Khazaka 2005), and we believe that possible salt adsorption on the skin surface had a marginal effect on our measurements. In the present study, the average variation coefficient of the measured COFs was 5.1%. This value was higher than the variation coefficients found in experiments, in which normal loads and sliding motions were machine controlled (Sivamani *et al.* 2003*b*,*c*; Gerhardt *et al.* 2008), but indicated a sufficient sensitivity and reliability of the 'direct touch' *in vivo* friction measurement method.

5. CONCLUSIONS

Skin analysis was combined with *in vivo* friction experiments on a force plate to study the effect of skin hydration on skin–textile friction. In a physiologically relevant range, friction increased linearly with skin hydration. Surprisingly, the influence of moisture on skin friction was more pronounced in women. Between epidermal moisture and skin elasticity, as well as elasticity and skin–fabric friction, no significant correlations were found. From very dry to normal skin conditions, friction increased typically by 26% in men and 43% in women. Measured against wet fabric, friction was more than two times higher than in the natural skin condition. Therefore, friction and moisture reduction remains a key measure in wound prevention strategies. The exact physical chemistry and biochemistry of bathing, as well as SC hydration mechanisms, are still to be explored in detail.

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