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Effects of sebum properties on skin friction

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Published in:
 Biosurface and Biotribology

DOI:
[10.1049/bsbt.2019.0015](https://doi.org/10.1049/bsbt.2019.0015)

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Document Version
 Publisher's PDF, also known as Version of record

Publication date:
 2020

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

Korbeld, K. T., Klaassen, M., Jobanputra, R. D., de Vries, E. G., & Masen, M. A. (2020). Effects of sebum properties on skin friction: Investigation using a bench test. *Biosurface and Biotribology*, 6(2), 43-47. <https://doi.org/10.1049/bsbt.2019.0015>

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ISSN 2405-4518

Received on 21st May 2019

Revised on 30th January 2020

Accepted on 26th February 2020

doi: 10.1049/bsbt.2019.0015

www.ietdl.org

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Abstract: The hydro lipid film is an emulsion of sweat and sebum that covers the surface of the human skin and affects the tribological properties of the human skin. This study investigates the effects of the composition of the sebum on the average coefficient of friction. A range of simplified sebums was developed and the friction behaviour was investigated. Five realistic sebums showed a strong variation in friction results, indicating that interpersonal differences in frictional behaviour might have their origin in differences in sebum composition. A more detailed investigation employing controlled variations of individual ingredients showed that friction is highly sensitive to the amount of squalene in the sebum. The amount of fatty acids in the sebum also showed some effects, whilst the amount of cholesterol does not appear to be relevant for the friction behaviour. The main new outcome from this study is that the composition of sebum has a significant effect on the friction response of skin in ways that are currently not yet fully understood.

1 Introduction

The skin is the largest organ of the human body, covering $\sim 2 \text{ m}^2$ and is an important interface with the outside world. During daily activities, skin interacts with a range of products such as clothing, hand tools and prosthetics. During this interaction, normal and shear forces are transmitted through the skin-product interface. These shear forces are the result of an interplay between the surface and the material properties of both the skin and the respective counter surface, the local environment, as well as the operational parameters such as the contact pressure and the sliding velocity. The forces acting on the skin are also known to potentially cause discomfort [1–5] and may even result in tissue injury such as blisters, tears and ulcers [6–10]. The effects of these parameters have been described extensively in literature and have been summarised by Derler *et al.* [8].

Various researchers, including [11–17], have previously described a qualitative correlation between the moisture content of the skin and the frictional response. Recently, Gupta [18] employed Fourier transfer infrared (FTIR) spectroscopy techniques to obtain an unambiguous quantification of the amount of moisture in the skin. By combining these in-vivo FTIR spectroscopy results with in-vivo tribometry obtained on a number of volunteers, they provided quantification of these previous qualitative findings on the effects of water on friction. Additionally, they investigated the role of skin lipids and found that for ‘untreated skin’, i.e. when the skin was not cleaned or prepared before performing measurements, the amount of lipids on the skin appears to not significantly affect the friction in skin-object interactions. This was more or less consistent with findings presented in [14, 16, 19, 20]. Pailler-Mattei *et al.* [20] showed skin in the ‘normal state’ to have elevated adhesion compared to skin from which the lipids have been removed, whilst Cua *et al.* [11] and Gupta [18] described finding a moderately weak correlation between friction and the skin surface lipid content, but only at a selected number of anatomical locations. A third finding by Klaassen [19] was that the mechanical characteristics and the composition of skin sebum are correlated with friction.

In all this, it should be noted that there is a distinct difference between results obtained in vivo and results obtained using skin substitutes or mimics. When conducted appropriately, in-vivo experiments benefit from relevance to real-life situations, but their

repeatability is typically fairly low, with large variation in obtained friction coefficients depending on the individual characteristics and the anatomical region at which measurements are made [8]. The above-mentioned relationships between skin moisture content and friction as well as skin surface lipid content and friction [19] have a correlation coefficient r of about 0.7–0.8 (i.e. $r^2 \simeq 0.5$ to -0.65), which, although low, is considered typical for a significant correlation for tribology results obtained in vivo. It can be concluded that the characteristics of the skin sebum layer affect friction, but at present it is not known to what extent. In this study, we aim to further investigate these results by performing friction tests using a range of controlled sebum compositions.

2 Materials and methods

The objective of the present study is to improve our understanding of the effects of composition of sebum on frictional response of the skin. The approach taken in this study is to develop a range of sebum mixtures and investigate their effects. In this study, a laboratory-based setup is preferable over an in-vivo approach as it facilitates direct comparison without introducing any additional complicating factors or variations, e.g. as the result of interpersonal differences.

2.1 Methods, specimens and experimental conditions

The employed experimental setup was an HFRR rig (PCS Instruments, London, UK), schematically shown in Fig. 1. The device generated a linear reciprocating motion between a stationary soft polymeric skin mimic made of polydimethylsiloxane (PDMS) and a moving glass counter surface. The PDMS specimen represents skin tissue and is used as the bottom (flat) specimen to act as the base for sebum. The PDMS has a hardness of 40 Shore A and a Young’s modulus of 1.3 MPa, meaning its stiffness is of a similar magnitude to that of human skin. A glass lens (Edmund Optics) with a radius of curvature of 16.43 mm was employed as the reciprocating upper body. A dead-weight load of 100 gf (0.98 N) was applied. The PDMS-glass material combination and the applied load of 0.98 gf

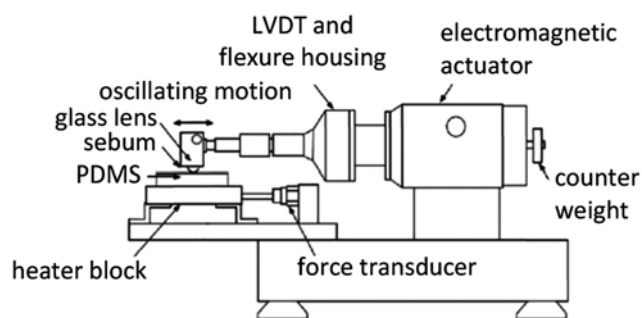


Fig. 1 Schematic of the HFRR rig

results in a maximum Hertz contact pressure of 124 kPa. This pressure is similar to what skin may experience in a wide range of normal, daily interactions such as wearing a face mask or sitting on a chair. The sliding velocity in skin–product interaction can vary from the order of a millimetre per second, e.g. in fine touch, to several metres per second, e.g. when engaging in sports activities such as sliding tackles. In this work, the velocity was set to 30 mm s^{-1} , as an intermediate value.

The friction force was measured using a piezoelectric force transducer and was recorded every second.

2.2 Artificial sebum

Sebum comprises a mixture of lipids, including squalene, wax esters, triglycerides, fatty acids, cholesterol and cholesterol esters [21]. It is well documented that the exact composition of sebum varies strongly between individuals [22] and thus could contribute to differences in frictional response.

Squalene is a cholesterol precursor and, together with wax esters, is unique to sebum within the human body. Although fatty acids are not exclusive to sebum like squalene or wax esters, they are present in sebum in much higher quantities than elsewhere in the body. Furthermore, the fatty acids in sebum show some unique characteristics, such as like sidechains, that are not found in the fatty acids elsewhere in the body. The exact role of each component in sebum is not clear, but sebum appears to be important in hair growth as well as moisture retention. The cell membrane naturally contains cholesterol and cholesterol esters and when the cell ruptures to release squalene, fatty acids, wax esters and triglycerides, minor amounts of cholesterol and cholesterol esters are secreted [22, 23].

2.2.1 Development of artificial sebums: Various steps were taken to create an accurate artificial sebum to investigate the tribological or pharmaceutical properties of the hydro lipid film [21, 24].

Table 1 Composition of the initial sebum used for measuring the effect of minor variations in layer thickness

Sebum ID	Composition, wt%			
	Squalene	Lanolin	Glyceryl trioleate	Palmitic acid
IAS	10	25	35	30

Table 2 Composition of the five representative artificial sebums (RAS) with controlled composition

Sebum ID	Composition, wt%					
	Squalene	Wax	Triglyceride	Fatty acids	Cholesterol	Cholesterol esters
RAS I	15.3	25.5	42.7	15.5	1.0	–
RAS II	13.5	27.0	34.0	23.8	1.7	–
RAS III	12.4	26.8	59.3	0.0	1.5	–
RAS IV	20.3	25.8	16.4	33.6	3.9	–
RAS V	13.9	19.3	65.0	1.2	0.6	–

Initial artificial sebum: An initial artificial sebum was developed based on the previous work on skin tribology [25], see also [26–28]. This sebum comprised lanolin, squalene, glyceryl trioleate and palmitic acid, as indicated in Table 1. All components were acquired via Sigma Aldrich.

In this recipe lanolin, which is essentially extracted sheep sebum, is the source of fatty acids, wax esters as well as minor amounts of cholesterol and cholesterol esters. However, using it as the source of several important sebum ingredients makes it impossible to vary these components independently and thus study their individual effects on the frictional response. Additionally, lanolin has the downsides of being chemically rather complex and having a highly variable composition [29], meaning that batch variations may induce differences between experimental results. Therefore, this initial artificial sebum mixture did not allow drawing any unambiguous conclusions regarding the contributions of the individual ingredients. This *initial artificial sebum* was only used in a set of initial experiments in which the sensitivity of the measurement results to variations in sebum layer thickness was assessed.

Representative artificial sebum: To analyse the effects of variations in human sebum on the observed friction, five different artificial sebum compositions were defined with more control of their ingredients, based on the review presented by Lu *et al.* [21]. These artificial sebum mixtures comprised varying amounts of squalene, palmitic acid and glyceryl trioleate, whilst the lanolin from the initial recipe was replaced by paraffin, which is a wax-like hydrocarbon that lacks ester bonds. The benefit of using paraffin is that it is a well-defined substance with similar mechanical properties to wax ester that is easily available and provides an ease of handling. These benefits were considered to outweigh the downside of not accounting for the possible characteristics and interactions provided by the ester bonds.

Cholesterol was added as an individual component, whilst cholesterol esters were not added to the artificial sebum as they are only present in real sebum in negligible concentrations. The resulting five recipes provided a well-defined range of sebum specimens that enable easy adjustment of the relative amounts of each component. Table 2 presents the five artificial sebum compositions used in this work, based on [21].

Each sebum mixture was produced by weighing the respective components, combining them and heating the mixture to 65°C to melt, followed by stirring to create a homogeneous fluid mixture. The samples were subsequently applied to the PDMS substrates following the procedure described later.

Controlled variations of ingredients: The friction results obtained using the five ‘representative artificial sebum’ (RAS) specimens with controlled compositions defined above provided useful information on frictional variations that may be expected in in-vivo situations. However, as all five recipes were significantly different it was not possible to identify which specific component can be related to these variations in friction. To more accurately identify the effect of each individual component and pinpoint the cause of the differences between the five sebum mixtures, a set of additional sebum specimens were produced where single ingredients were incrementally increased, whilst the relative ratio between the other components was kept constant. The three ingredients that were investigated in more detail in this set of experiments were squalene, fatty acid and cholesterol. Base stock mixtures were developed for each of these three ingredients, whilst the compositional range for each variable ingredient was selected

Table 3 Composition of the stock sebum mixtures used to investigate variations in composition

Variable Ingredient	Composition of base stock mixture, wt%					Range (wt%) of variable ingredient
	Squalene	Wax	Triglycerides	Fatty acids	Cholesterol	
squalene	10	30	45	15	2	10–30
fatty acids	15	35	50	0	2	0–35
cholesterol	13	31	43	13	0	0–4

based on the extreme values listed by Lu *et al.* [21]. For each wt% increment of the variable ingredient, the coefficient of friction was measured five times. All measurements were performed at 34°C, which is the temperature of skin under 'normal' conditions.

2.2.2 Specimen preparation: The sebum mixtures were applied onto a substrate of PDMS. Before the sebum was applied, the PDMS was cleaned using detergent and tap water and rinsed with isopropanol to remove any remaining lipids. The samples were then rinsed once more with tap water and dried to make sure no residue of detergent or ethanol was left. The cleaned PDMS sample was then cut into 20 mm × 50 mm rectangles.

Layer application: Various researchers report the use of chloroform or a chloroform/methanol mixture as a solvent for the lipids, thus allowing control of the amount of sebum deposited onto the surface [30, 31]. However, the use of chloroform presents an inherent health and safety hazard and therefore it was opted to not dissolve the sebum mixture, but to directly apply the sebum to the PDMS specimens. The aim was to apply similar amounts of sebum as found on the human skin and thus to provide a much faster and safer protocol.

Two different methods were used to apply the sebum mixtures to the PDMS base. For the initial set of experiments, in which the focus was on studying effects of minor variations in layer thickness, the layers were created by using a Micrometre Adjustable Film Applicator (Sheen instruments, UK). This was done by first calibrating the applicator height bar to the thickness of the PDMS specimen, then applying an excess of the sebum mixture to the PDMS specimen and finally raising the height of the applicator bar to the required film thickness and scraping off any excess sebum to create a layer of the desired thickness.

In the subsequent tests, sebum layers were applied by depositing 10 mg of the sebum mixture on the 50 mm × 20 mm PDMS specimen in order to create a layer of 10 µg/mm². The sebum mixtures were applied to the PDMS using the flat part of a spatula until the entire surface was covered and the layer appeared uniform to the naked eye. This procedure was facilitated by the PDMS specimens being opaque, meaning thickness variations were easily observed. Sebum layers produced using this method were approximately two to ten times thicker than those found on the body, but this was the thinnest amount that could reliably and repeatably be applied to the PDMS specimens.

2.3 Experimental programme

The executed experimental programme started with an initial study in which the effects of sebum layer thickness were investigated. Subsequently, the frictional responses for five artificial sebum specimens with controlled compositions were determined at both room temperature and an elevated temperature. Following these initial experiments, a study into the compositional aspects of sebum on friction was executed.

2.3.1 Sensitivity to layer thickness variations: To investigate the effect of minor variations in layer thickness on the measured friction, an initial experimental programme was performed with a single artificial sebum that was applied at controlled thicknesses. For these tests, the initial lanolin-based sebum recipe was used, with a composition as indicated in Table 3.

The components were weighed, combined and heated to 65°C to create a homogeneous mixture. The micrometre adjustable film

applicator was used to create layers with thicknesses of 5, 10 and 15 µm. Friction measurements were performed at room temperature in triplicate for each layer thickness.

2.3.2 Temperature effects: The five representative artificial sebums were tested both at room temperature (22°C) and at the typical skin temperature of 34°C. Each measurement was repeated five times.

2.3.3 Controlled variations in composition: Fourteen different sebum recipes were developed based on the base stocks presented in Table 3. Experiments were carried out at the skin temperature of 34°C. Each measurement was repeated five times.

3 Results

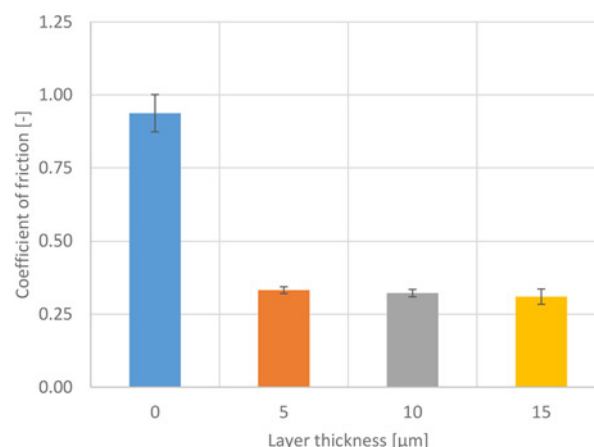
3.1 Effect of thickness

The coefficient of friction measured for various layer thicknesses of the 'initial sebum recipe' is shown in Fig. 2. The average coefficient of friction for any of the sebums is ~0.32, with a negligible effect of sebum layer thickness. The measured coefficient of friction was 0.33, 0.32 and 0.31 for sebum thicknesses of 5, 10 and 15 µm, respectively. Repeatability, as represented by the error bars was very good. As a negative control, the friction on a cleaned PDMS specimen was also measured. As expected, the coefficient of friction of the clean PDMS specimen was much higher, being over 0.90, and showed more variation.

From these results it can be concluded that the obtained frictional measurements in the system are insensitive to minor variations in layer thickness.

3.2 Five different representative human sebum recipes

PDMS samples with a 10 µg mm⁻² layer of sebum were made for each sebum mixture and tested at both room temperature (22°C) and a typically occurring temperature of the skin of 34°C. Fig. 3 shows the time-dependent frictional response for the five realistic artificial sebums at room temperature. Large differences can be observed between the various sebums; RAS I, RAS III and RAS

**Fig. 2** Effect of sebum thickness on measured coefficient of friction

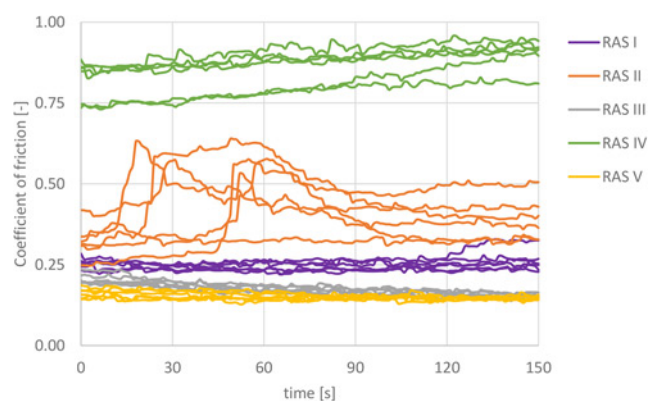


Fig. 3 Evolution of the coefficient of friction in time for the five realistic artificial sebums at 24°C

V show constant values with good repeatability. In contrast, the two sebums with a relatively high fatty acid content and relatively low triglyceride content (RAS II and RAS IV) show a large variation between tests, whilst RAS II also shows large fluctuations in time.

Fig. 4 shows the average friction results obtained for the five sebums at room temperature, represented by the non-patterned bars, and those obtained at 34°C, represented by the diagonally patterned bars. For most of the artificial sebums there is no significant effect of temperature on the obtained results, except for RAS II and RAS IV. RAS II showed a significantly reduced friction, in combination with much better repeatability between tests, whilst RAS IV at 34°C showed a similar average friction as at 24°C, in combination with significantly increased fluctuations.

3.3 Individual components

The effects of squalene, fatty acids and cholesterol on the coefficient of friction were investigated in more detail by performing tests using controlled sebum compositions.

3.3.1 Squalene: Sebum mixtures with 10, 15, 20 and 30 wt% were investigated, whilst the amounts of other ingredients were kept constant. The coefficient of friction remained low at about 0.20 for all compositions, except for the recipe with 20 wt% squalene (Fig. 5). At 20 wt% squalene, the friction was significantly higher and the individual measurements showed significantly larger variations. This corresponds with the results previously obtained for RAS IV, which also had a squalene percentage of 20% and showed poor repeatability. RAS IV was the only recipe of the five defined representative artificial sebums that had a squalene concentration higher than 15%.

From in-vivo investigations, Gloor [32] [in German, see also Elkhyat [33]] concluded a linear correlation between wettability

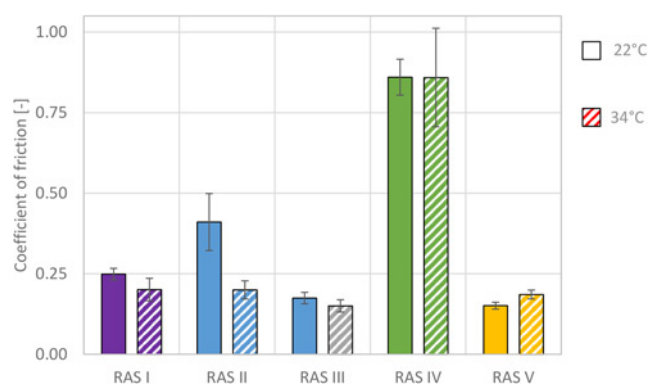


Fig. 4 Average coefficient of friction for five different representative artificial sebums, also showing the effects of temperature

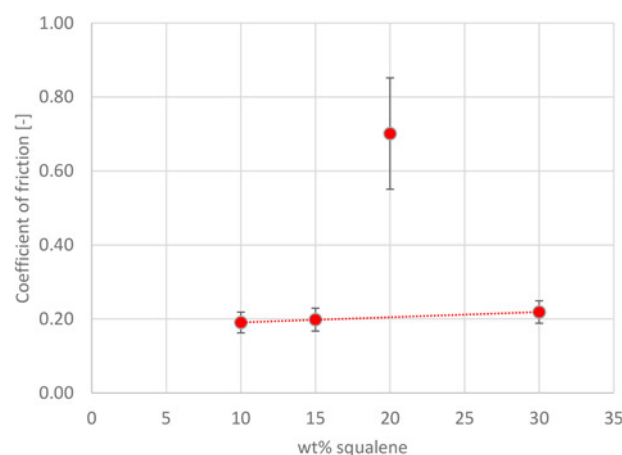


Fig. 5 Average coefficient of friction for various amounts of squalene

and squalene content of skin. Chen [34] discusses the effects of lipid films on friction, describing lower friction values due to thicker films reducing the interfacial shear strength, whilst the formation of meniscus bridges increases friction. It is at present unclear if these possible explanations relate to the observed sharp peak at 20 wt% squalene, or to the sharp decline at 30 wt% squalene. Explaining the spreadability of a range of emollients on skin, Gore *et al.* [35] lists aspects including the polarity, the physical and chemical nature of the layers and their physical state as factors potentially having an important effect.

3.3.2 Fatty acids: For fatty acids, the employed concentrations were 0, 5, 15, 25 and 35 wt%. Much like the results obtained for squalene, most recipes resulted in a repeatable coefficient of friction of ~0.20 (Fig. 6). However, the sebum with 25% fatty acids resulted in a slightly elevated coefficient of friction of about 0.27, where the expectation based on interpolation of the other measurements would indicate a friction of $\sim 0.21 \pm 0.01$. The measured friction traces also showed reduced repeatability as indicated by the relatively large standard deviation of 0.15.

3.3.3 Cholesterol: Cholesterol only appears in sebum in minor amounts and thus a fairly small range between 0 and 4 wt% was investigated at increments of 1 wt%. All measurements showed a low average coefficient of friction of between 0.16 and 0.18 with good reproducibility (Fig. 7). Overall, the concentration of cholesterol within this range appeared to have no significant effect on the coefficient of friction.

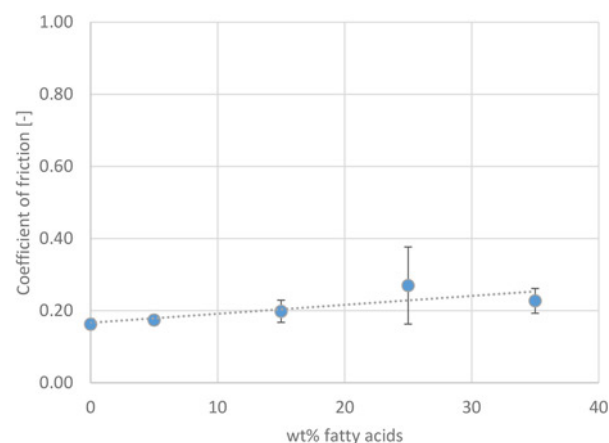


Fig. 6 Average coefficient of friction for various amounts of fatty acids

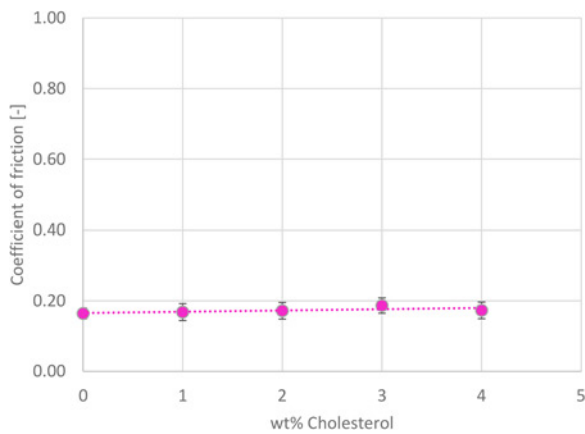


Fig. 7 Average coefficient of friction for various amounts of cholesterol

4 Conclusions

Simplified sebum recipes comprising the main ingredients of human sebum were made. Using a high frequency reciprocating rig, the effect of the composition on the tribological properties of the sebum was investigated. The main new outcome from this study is that the composition of sebum has a significant effect on the friction response of skin in ways that are currently not yet fully understood. The response shows some rather striking non-linear behaviour and more investigation of these effects, using both in-vitro and in-vivo approaches, is needed. Furthermore, it should be noted that the utilised sebum recipes were fairly simple and did not contain wax esters nor cholesterol esters. In addition, the ratio between saturated and unsaturated lipids was not considered. These may also have a significant effect on the frictional behaviour of in-vivo sebum. Nevertheless, the following conclusions could be drawn:

- (i) Increasing sebum thickness only slightly decreases the coefficient of friction.
- (ii) Differences in composition of the sebum appear to have a significant effect on the coefficient of friction.
- (iii) When present in a percentage of ~20 wt%, squalene exhibits a strongly increased coefficient of friction in combination with poor repeatability. This is not seen at other amounts of squalene. The underlying mechanism to this behaviour is presently unclear.
- (iv) Fatty acids slightly increase the coefficient of friction and its unpredictability when present in a percentage of ~25%. The underlying mechanism is unclear.
- (v) Cholesterol does not appear to have a significant effect on the coefficient of friction when present in concentrations relevant to human sebum.

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