Aspects of Shaving
Friction

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A THESIS SUBMITTED FOR THE DEGREE OF
DOCTOR OF ENGINEERING IN MICRO AND
NANOMATERIALS AND TECHNOLOGIES
(MiNMaT)

UNIVERSITY OF SURREY

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MAY, 2015
Abstract

Shaving is an everyday act for many people and Gillette is at the forefront of this market. The complex process of designing a razor involves understanding the interaction between the cartridge and the face which are complicated systems in their own right. Wet shaving is a complex tribological process for which the mechanisms and parameters are not well understood. The time and high cost associated with designing razors are a major driving force for developing a technical model of shaving. Friction has been identified as an important parameter influencing consumer relevant attributes such glide and comfort. This thesis focused on breaking the problem down into two key areas, skin friction and hair cutting friction. By combining in-vivo and in-vitro testing capabilities, the key parameters affecting skin friction were determined and quantified. Due to the limited knowledge of the relative contribution of adhesion and deformation friction to total friction in the biotribology field, this thesis has confirmed past results and expanded on previous knowledge regarding the relative proportion of adhesion and deformation in three lubrication cases, namely, dry, water and oil contacts. Empirical models of skin friction for these three cases were developed to estimate the relative proportion of adhesion and deformation friction. The primary parameters affecting relative proportion of adhesion and deformation included the contact lubrication, probe material, sliding speed, and probe geometry. Further, the results indicated for the oil contact case, for high normal loads and sliding speeds, deformation friction contributed as much as 50% of the total friction. Hair cutting friction was also investigated focusing on two parameters, hair density and hair cutting profile. These two parameters significantly affected hair cutting friction, where increasing hair density and the area under the curve (hair cutting profile) increased hair cutting friction significantly. Two case studies were considered that combined data from skin friction and hair cutting to estimate the relative proportion of adhesion, deformation and hair cutting friction to shaving friction. The results showed, for contacts with water as a lubricant, hair cutting and adhesion friction contribute on average the same proportion (40-40%) and depends on the type of hair cutting profile considered. For contacts with oil as a lubricant, relative contribution of hair cutting friction significantly increases and can be as high as 80% of the shaving friction depending on the hair cutting profile considered.
ACKNOWLEDGEMENTS

To be writing this acknowledgement in itself brings me to tears and reminds of the momentous steps I have taken to be where I am today. I would like to first thank my parents Saynab and Abdirahman who have been through a lot with me and I am eternally grateful for their unwavering support. I would like to also thank my siblings who have given me moral support throughout my doctorate studies. My industrial supervisor Dr. Alisons Riches who has been my backbone from the start of this journey and I would like to thank her sincerely for her patience and believe in me as well as her insightful and engaging discussions on the work I have undertaken. I would like also to extend my sincere gratitude to my other industrial supervisor Dr. Matthias Gester, who widened my understanding and researching capacity with his direct and global view of the problem. My academic supervisors Prof. Paul Smith and Prof. Julie Yeomans have also set the highest academic standard for me to aspire to and I hope this thesis does justice to their efforts. At times, the difficult advice I received from them might have appeared to have disheartened me but it always drove me to be a better researcher and for that I am truly grateful. I would like also to thank Dr. Bala Amavasai, Arafat Bhallizada and Paul Clarke for their efforts and advise on many of the instruments that have been key to my work. Last, but not least, all of my colleagues at Gillette, it has been a wonderful experience and every single person I have interacted with has been exceptional in their desire to help and discuss work or otherwise.
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<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>$\alpha$</td>
<td>Hysteresis loss</td>
</tr>
<tr>
<td>$(lrf)_c$</td>
<td>Loss-radius factor (cylinder)</td>
</tr>
<tr>
<td>$(lrf)_s$</td>
<td>Loss-radius factor (sphere)</td>
</tr>
<tr>
<td>$(lrf)_{cm}$</td>
<td>Modified Loss-radius factor (cylinder)</td>
</tr>
<tr>
<td>$(lrf)_{sm}$</td>
<td>Modified Loss-radius factor (sphere)</td>
</tr>
<tr>
<td>$F_T$</td>
<td>Total friction</td>
</tr>
<tr>
<td>$F_A$</td>
<td>Adhesion friction</td>
</tr>
<tr>
<td>$F_D$</td>
<td>Deformation friction</td>
</tr>
<tr>
<td>$F_R$</td>
<td>Rolling Friction</td>
</tr>
<tr>
<td>$F_S$</td>
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</tr>
<tr>
<td>$F_B$</td>
<td>Bearing Friction</td>
</tr>
<tr>
<td>$W$</td>
<td>Normal Load</td>
</tr>
<tr>
<td>$a_c$</td>
<td>Cylinder Contact Radius</td>
</tr>
<tr>
<td>$a_s$</td>
<td>Sphere Contact Radius</td>
</tr>
<tr>
<td>$R_c$</td>
<td>Cylinder radius</td>
</tr>
<tr>
<td>$R_s$</td>
<td>Sphere Radius</td>
</tr>
<tr>
<td>IEHL</td>
<td>Isoviscous elastohydrodynamic lubrication</td>
</tr>
<tr>
<td>PTFE</td>
<td>Polytetrafluoroethylene</td>
</tr>
<tr>
<td>DFD</td>
<td>Dynamic friction device</td>
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</tbody>
</table>
1 INTRODUCTION

1.1 Background

Shaving is an everyday act for many people and Gillette has been at the forefront of the shaving market from the early generations of safety razors to the modern multi-bladed razor brands such as Fusion, Venus and Proglide. Gillette’s Fusion brand has been generating revenues in excess of a billion dollars since its introduction in 2006. Currently, manufacturers offer an array of products for both genders, with features tailored to provide the best shaving experience. The latest male razor, Proglide, has in excess of 30 components, including precision engineered blades, an advanced lubricant strip and elastomeric guard.

The complex process of designing a razor involves understanding the interaction between the cartridge and the face, which are complicated systems in their own right as seen in figure 1-1. A marketable razor has to be superior to its predecessor e.g. Fusion to Proglide. The judgement of superiority is based on established subjective criteria, including glide and comfort scores from users.

![Figure 1-1: A photograph of a razor cartridge (left) and schematic illustration of skin with hair and lubricant (right)](image)

Shaving science can be broken down broadly into two areas of research i.e. subjective measures and technical measures. The subjective measures attempt to understand how the razor, in particular, the cartridge is perceived in-shave and post shave. Consumers are trained to use specialised terminology to communicate the ‘feel’ of the shave with terms such as glide, pull and tug, comfort, closeness etc. These are further complemented by
visual observations of the post shave skin such as redness, missed hairs, cuts, etc. The subjective measures are indicators of the performance of the razor and determine its success. The subjective measures cover both ‘positive’ and ‘negative’ effects of shaving and for this reason, technical measures are required to quantify the shaving stroke, in order to retain the positive attributes and mitigate the negative ones. Therefore, technical measures strive to understand the interaction between the cartridge components, skin, hair and lubricant, in terms of their surface, chemical and mechanical properties. Ultimately, the goal is to correlate the technical measures with subjective measures in order to achieve a desired effect i.e. a comfortable, close and clean shave.

Wet shaving is primarily carried out with a lubricant, which in the simplest form can be just water. As wet shaving is a complex tribological process for which the mechanisms and parameters that control the process are not well understood, the design time is long and costly. This drives the need to develop a technical model of shaving. Such a model would reduce the need to develop and test countless designs thus bringing products to market more quickly and more cost effectively.

Friction has been identified as one of the technical parameters that correlates with key subjective measures such as glide and comfort. By understanding the parameters controlling shaving friction and linking them to subjective measures, the shaving experience can be improved. Shaving friction is attributed to two main interactions; the first is the interaction between the blades and hair (skin in some cases, leading to cuts) and the second is the interaction between the rest of the cartridge and skin (the cartridge also interacts with hair). These interactions are not well understood, especially the contribution of hair cutting to shaving friction. Although, there is a vast body of literature data on skin friction (without hair), owing to the complex nature of friction, is not conclusive and thus this is an ongoing active area of research.

As a first approximation in this study, the contribution of hair cutting and skin friction to shaving friction are considered to be independent and these components are investigated in isolation. This is because there are limited data for both of these components that are relevant to shaving. By considering each component separately, the foundational work can be developed before introducing further complexities associated with interactions.
In this study the substrate of interest is the face, which is a difficult area to probe with traditional tabletop tribometers, hence, specialised instruments and methods are employed to investigate shaving friction. Two primary testing approaches are used. The first is *in-vivo* testing on human subjects and the second is *in-vitro* testing, which uses substrates designed to mimic skin and hairs extracted from human subjects.

The overarching aim is to develop a technical model of shaving friction, in terms of two components, skin friction and hair cutting friction.

### 1.2 Aims of the Project

From this overarching aim, at the outset of the project, several intermediate stages were identified:

- To identify key parameters affecting skin friction
- To identify key parameters affecting hair cutting
- Develop test methodologies to quantify their effect
- Develop a model of shaving friction based on skin friction and hair cutting friction.

The aims defined here will be refined once the literature has been reviewed.

### 1.3 Structure of the Thesis

This thesis is organised into seven chapters including this introduction. Chapter two is a comprehensive review of the literature focusing on skin’s mechanical properties, skin friction and hair cutting friction. Chapter three discusses the materials and instrumentation utilised to investigate the mechanical properties of skin and skin friction. This chapter highlights the methods and techniques used to justify some of the choices made, in particular, whether the skin mimic is a suitable *in-vitro* substrate to investigate skin friction. Chapters four and five detail the two primary set of experiments carried out to investigate key parameters affecting skin friction. The first set of experiments was *in-vivo* and focused on measuring skin friction on human subjects and determining the parameters controlling this process. The second set of experiments extended this approach but instead utilised skin mimics to achieve control over the testing process and determine parameters affecting skin friction. Chapter six covers the two models developed for skin friction and hair cutting friction. These models are based on the relative contribution of adhesion and deformation friction to total friction and the
parameters affecting these proportions. Further, the chapter considers two case studies combining skin and hair cutting friction to gain insights into the relative contribution of adhesion, deformation and hair cutting friction i.e. shaving friction. Chapter seven summarises the results from the thesis detailing conclusions, recommendations and future work.
2 LITERATURE REVIEW

2.1 Introduction
Research into skin friction is extensive in the academic and industrial literature, and constitutes a large part of the growing area of biotribology. This area of tribology touches every aspect of our lives from movement in our synovial joints, bathing and showering, combing hair, brushing teeth, the tactile feel of clothing, shaving and all contact internal/external to the body (Dowson, 2009).

Friction is traditionally a difficult parameter to quantify and is not a material property but rather a system property of the interacting materials. For traditional engineering materials, typically a coefficient of friction (COF) value is quoted for the pair of interacting materials. For biological materials the situation is more complex principally because of the variable nature of the material.

The scope of this literature review is the exploration of key parameters affecting skin friction. The review will highlight the mechanical properties of skin and their dynamic nature, the surface properties of skin, the wide range of COF values quoted, the probes used as well as proposed mechanisms controlling skin friction. Further, in the context of shaving, some of the properties of hair and the mechanisms controlling hair cutting are discussed.

2.2 Overview of Skin

2.2.1 Structure of Skin
Skin is the largest organ of the body providing the first line of defence against the environment. Skin is composed of three primary layers namely, epidermis, dermis and subcutaneous fat (hypodermis). Embedded in the primary layers are sweat glands, hair, blood vessels and sensory nerve endings contributing to the overall structure of the skin (figure 2-1).

The epidermis is composed of outward moving cells called keratinocytes formed through cell division in the basal layer of the epidermis. The epidermis varies with anatomical site, age, gender, skin type, pigmentation, blood content and life style choice (e.g. smoking). There are two primary layers in the epidermis, the stratum corneum and the viable
epidermis. The stratum corneum is 10-20 µm thick provides a barrier against water loss and protection from pathogens in the environment. The structure of the stratum corneum is described as brick and mortar in which corneocytes are held together in lamellar lipid sheets. The stratum corneum contains 15%wt water compared with 70%wt for most body tissue (Marks, 2004) (River Diagnostics, 2015). Its properties are dependent on temperature and humidity affecting its mechanical and frictional properties. The water content of the stratum corneum is determined by two mechanisms i.e. diffusion of water from the dermis and environment (humidity), and evaporation to the environment. Water diffuses from the underlying dermis at a comparably higher rate compared with the diffusion of water through the epidermis (stratum corneum) to the environment. This ensures that water from underlying tissue is not lost (barrier to water loss). Further, temperature, humidity and air flow influence the rate of evaporation, where high temperature, low humidity and flowing air cause the stratum corneum to dry out (Blank, 1951). The variable nature of the stratum corneum due to the environment and the presence of lipids on its surface greatly contributes to the wide range of friction values measured on skin.

Figure 2-1: Schematic diagram showing the structure of skin (taken from Dąbrowska et al., 2015)
The viable epidermis is 80 µm thick and composed of the stratum basale, stratum spinosum and granulosum. The lowest layer, the stratum basale of the epidermis is connected to the dermis through a basement membrane to form the epidermal-dermis junction. This connection anchors the epidermis to the dermis.

The dermis layer is made up of two layers; an upper layer, the papillary, which accounts for 10% of the dermis thickness and is made up of collagen fibrils 20-40 nm in diameter contained in thicker collagen fibres of 0.3-3 µm in diameter. The lower layer of the dermis, the reticular, is composed of collagen fibrils with diameters in the range 60-100 nm. The dermis layer dominates the mechanical behaviour of the whole skin and is 1-4 mm in thickness. The subcutaneous fat layer (hypodermis) is made up of loose fatty connective tissue with thickness > 1 mm, which varies with anatomical site. This complex multi-layer structure of skin leads to a complex mechanical response that displays both elastic and viscous behaviour, so called viscoelastic behaviour due to the stretching of fibres and the expelling of fluid in the matrix, leading to a rate dependent stress and strain response. As well as these features, skin shows hysteresis between loading-unloading profiles, stress relaxation (constant strain) and creep (constant stress).

2.2.2 Topography of Skin

The surface of skin is characterised by furrows, follicular orifices, sweat pores and protruding corneocytes (figure 2-2). There are several levels of furrows, characterised by their depth. The primary furrows are 70-200 µm deep and extend in at least two directions. The edges of primary furrows are where hair follicular orifices are located. Secondary furrows are 20-70 µm deep and contain sweat pores. The tertiary furrows separate sets of corneocytes. Furrow structure on skin varies with age and gender.

The furrow network is believed to serve a mechanical function where the application of load allows furrows to straighten (unfold), protecting the underlying cells. The highest extensibility is seen perpendicular to the direction of the main furrow.

The anisotropic structure of skin is due to natural tension characterised by Langer's lines, contours (e.g. nose-cheek junction) and wrinkles. Langer’s lines correspond to preferential alignment of collagen and elastin fibres (stretched) in the direction of the lines and therefore, extensibility is greatest perpendicular to these lines (see figure 2-3).
Figure 2-2: Image of the right flexor forearm of a 23 years old male subject (Jacobi et al., 2004)

Figure 2-3: Langer's lines (taken from Maurel et al., 1998)
2.2.3 Mechanical Properties of Skin

The multi-layered structure of skin is anisotropic and inhomogeneous resulting in non-linear and viscoelastic behaviour. The mechanical response of skin is influenced by the skin layers probed, anatomical site, age of test subject, skin hydration, loading profile, loading direction and strain rate.

The mechanical properties of skin, particularly the Young’s modulus, have been studied by many researchers. Figure 2-4 shows summary data for Young’s modulus values as quoted in the literature for skin, separated into the constituent components reviewed by Derler et al., (2012) (based on five studies). The dermis is considered to be dominant in the overall mechanical behaviour of skin.

![Figure 2-4: Young's moduli of skin and its constituent components (SC = Stratum Corneum) (taken from Derler et al., 2012)](image)

<table>
<thead>
<tr>
<th>Layer</th>
<th>25% RH</th>
<th>98% RH</th>
<th>25% RH</th>
<th>98% RH</th>
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<tr>
<td>Stratum Corneum (SC)</td>
<td>25% RH</td>
<td>98% RH</td>
<td>25% RH</td>
<td>98% RH</td>
</tr>
<tr>
<td>Viable epidermis</td>
<td>25% RH</td>
<td>98% RH</td>
<td>25% RH</td>
<td>98% RH</td>
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<tr>
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<td>20-30</td>
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<table>
<thead>
<tr>
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<th>Shear Modulus G (kPa)</th>
<th>Indentation Young's Modulus E (kPa)</th>
<th>Tensile (Uniaxial) Young's Modulus E (kPa)</th>
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</thead>
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<tr>
<td>Stratum Corneum (SC)</td>
<td>30</td>
<td>600</td>
<td>0.04 – 10x10^6</td>
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<tr>
<td>Viable epidermis</td>
<td>30</td>
<td>n.a.*</td>
<td>6 – 10x10^4</td>
</tr>
<tr>
<td>Dermis</td>
<td>8</td>
<td>1-10</td>
<td>1 – 20,000</td>
</tr>
<tr>
<td>Hypodermis</td>
<td>24</td>
<td>20-30</td>
<td>n.a.*</td>
</tr>
</tbody>
</table>

Table 2-1: Young's modulus for the three primary layers of the skin (reproduced from Geerligs, 2009)
Table 2-1 summarises mechanical response of skin’s different layers based on a review of current in-vitro literature data by Geerligs, 2009. The complex structure of skin requires different mechanical testing techniques that characterise skin in different directions. Further, the various layers cannot be studied independently in-vivo therefore constituent skin layers are isolated and tested in-vitro. Testing was limited to small strains to stay in the elastic region. The shear modulus data were acquired using a rotational rheometer, where the skin samples were placed on the edge of a plate and rotated. Torque and angle of the sheared skin were measured and used to determine the shear stress and shear strain. The shear modulus was calculated using the equation $E = 3G$, where $E$ is the Young’s modulus and $G$ is the shear modulus. The uni-axial tensile testing data were measured by attaching two tabs to the sample and pulling them apart and the stress and strain determined from the force-displacement curves taking geometry into account. For indentation testing, a rigid probe was used to apply a known force and the stress and strain calculated. It is clear from table 2-1 that each layer has a wide mechanical response especially the stratum corneum, based on the testing method used and humidity of the environment.

The outermost layer of the epidermis, the stratum corneum, is influenced by conditions in the environment such as the temperature and relative humidity. The elasticity of the stratum corneum is seen to decrease with decreasing relative humidity and temperature. The variations reported in the Young’s modulus (in-vitro) data as a function of humidity (figure 2-5) could possibly be due to the condition of the samples, the species (mammals) used, the environmental conditions and the measurement instruments used and the processing chemicals used to extract and clean the skin samples. The figure nonetheless illustrates that humidity influences the elasticity of the stratum corneum (Geerligs, 2006).
Silver and co-workers investigated the stress-strain behaviour of the dermis *in vitro*. The measurements were carried on skin taken from human cadavers in the age range of 47-86 years old (thoracic and abdominal skin). Tensile measurements were carried out on the samples using an Instron mechanical testing machine.

The elastic and viscous responses seen in figure 2-6 were calculated from the total response. Samples were stretched to each strain increment and the stress measured (total stress). Then, the stress was allowed to decay to equilibrium and this was taken to be the elastic stress. The difference between the total stress and elastic stress is the viscous stress. The stress-strain behaviour of the dermis involves three stages, as illustrated in figure 2-7 (Holzapfel, (2000), Silver *et al.*, (2001)):

1. For strains up to 0.3, the collagen network offers little resistance to deformation and the behaviour is determined by elastic fibres.
2. For strains between 0.3 -0.6 collagen fibrils offer greater resistance to deformation.
3. Above strains of 0.6 (yield and failure region) fibril defibrillation occurs (breakage of cross link between fibrils).
Studies on the mechanical properties of skin in-vitro have concentrated on the dermis since it is the dominant structural layer in the mechanical response of skin; little is known about the mechanical properties of the subcutaneous fat layer (Geerligs., 2009).
2.2.4 The Global Mechanical Response of Skin: *In-vivo*

Thus far, the data presented from the literature have illustrated the dynamic nature of mechanical properties of skin and its complex behaviour *in-vitro*. For this reason, researchers carry out measurements of mechanical properties relevant to their applications of interest.

For shaving, the overall viscoelastic response of skin *in-vivo* is of particular interest, since the skin during shaving is loaded primarily in two planes i.e. normal and parallel to the skin plane. Indentation has been adopted as the primary mechanical characterisation tool to capture key viscoelastic responses, namely stiffness, hysteresis and stress relaxation. This section of the literature focuses on data collected by P&G to characterise skin’s global mechanical response *in-vivo*.

Figure 2-8 shows *in-vivo* indentation measurements carried out using a 1 mm cylindrical steel probe at a rate of 3 mm/s on the forearm, cheek socket, cheek (bony part), chin and neck. Normal loads in the range of 0.2 – 2N were used. An Instron machine was used for the forearm measurements while for the other sensitive and difficult areas of the face, a bespoke instrument was used. The tests were carried out on seven panellists in the age range 20-61 years old.

The force displacement curves in figure 2-8 show the variable nature of skin response to normal loading within and across anatomical sites. The key feature of figure 2-8 is the non-linear response due to the multi-layer structure of skin. Thus, the stress as a function of strain behaviour is non-linear, resulting in a depth dependent modulus. This is the primary reason why the values for modulus quoted in the literature vary over several orders of magnitude (4.4 kPa to 57 MPa, Derler, 2012).
Hysteresis loss is defined as the energy difference between the loading and unloading portions of the force-displacement curve (see figure 2-9). From figure 2-9, the hysteresis loss of the forearm skin is on average 25% i.e. 25% of the energy is dissipated. This is comparable with data from Johnson et al., 1993, where a value of 24% at an indentation rate of 2.5 mm/s to an end loading of 2 N using a spherical probe was measured.

Figure 2-9: Loading and unloading profiles of the forearm, where the area between the two profiles represents hysteresis energy loss (Skin Research, Gillette, 2014).
Stress relaxation is measured by loading to an end displacement (fixed strain) and observing the stress response. A stress relaxation profile of the forearm is shown in figure 2-10 loaded for a duration of 20 seconds. The stress is initially seen to relax significantly but gradually the rate declines to reach a plateau as the time approaches 20 seconds.

Figure 2-10: Stress relaxation profile of the forearm skin (Skin Research, Gillette, 2014)

2.2.5 Summary of Mechanical Property Data for Skin

The data presented here have shown that there is a wide range of possible mechanical behaviours as skin is non-linear and anisotropic, inhomogeneous and viscoelastic. For this reason, the mechanical response of skin is greatly influenced by the layers probed, anatomical site, age, skin hydration, loading profile, loading direction and strain rate. These considerations play a role in the wide range of values quoted for the coefficient of friction (COF) of skin, which is discussed in the next section.

2.3 Friction

2.3.1 Definition of Friction

Friction can be defined as the force one surface or object encounters when moving over another. This can further be divided into static friction which is considered friction just before sliding occurs and dynamic friction, which is friction on sliding.

The interaction of hard-on-hard materials differs significantly from that of soft-on-hard or soft-on-soft material interactions. In this case, the razor (or probe) is hard whereas the skin is soft (viscoelastic). Thus, friction in this context refers to the surface adhesion friction, the surface deformation friction (skin bulging and ploughing) and the bulk
friction (hysteresis) due to viscous loss; the later is characteristic of viscoelastic materials.

Guillaume Amontons developed some of the basic laws of friction. They state the following:

1. Frictional force is proportional to normal load (equation 2-1)
2. Frictional force is independent of nominal surface contact area

\[ F = \mu W \]  

\text{Equation 2-1}

Where, F is the frictional force, \( \mu \) is the coefficient of friction (CoF) and W is the normal load.

This law is understood to apply to dry friction, particularly to metals in contact with each other. In addition to these two laws, another due to Coulomb states that friction is independent of the sliding velocity. It is important to note that the coefficients of static friction and dynamic friction will generally be different since the force needed to initiate sliding is typically greater than that required to maintain it.

Skin has been seen to deviate from these laws and it has been argued that this is due to the viscoelastic nature of skin and its surface variability (e.g. Sivamani \textit{et al.}, 2006).


### 2.3.2 Overview of Skin Friction

Research into skin friction has concentrated on understanding the dynamic CoF. Thus, any discussion in this section regarding CoF will be about dynamic CoF unless otherwise stated.

Skin friction studies in the literature have focused on broadly three categories: cosmetics and skin care products, dermatology in areas like wound healing and ageing, and finger pad friction in relation to touch sensation. This section of the thesis will focus on the key findings from these different areas of research.

A theoretical analysis by Wolfram, 1983, found the CoF to be inversely proportional to normal load. Reported values for the CoF of skin have ranged from around 0.1 on the abdomen using a Teflon probe to around 3 for hands on different rock surfaces. Table 2-2 summarises the variations in the measured values of the CoF.

<table>
<thead>
<tr>
<th>Author</th>
<th>CoF, µ</th>
<th>Probe Material</th>
<th>Probe</th>
<th>Motion of Apparatus and Maintenance of Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Naylor (1955)</td>
<td>0.5-06</td>
<td>Polyethylene</td>
<td>8 mm diameter, sphere</td>
<td>Linear reciprocating (static weights)</td>
</tr>
<tr>
<td>El-Shimi (1977)</td>
<td>0.2-0.4</td>
<td>Stainless steel (rough)</td>
<td>12 mm diameter hemisphere</td>
<td>Rotational (static weights)</td>
</tr>
<tr>
<td></td>
<td>0.3 - 0.6</td>
<td>Stainless steel (smooth)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Comaish and Bottoms (1971)</td>
<td>0.2</td>
<td>Teflon</td>
<td>15 mm diameter, annular ring</td>
<td>Linear reciprocating (static weights)</td>
</tr>
<tr>
<td></td>
<td>0.45</td>
<td>Nylon</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.3</td>
<td>Polyethylene</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.4</td>
<td>Wool</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Koudine et al. (2000)</td>
<td>0.24 (dorsal forearm)</td>
<td>Glass</td>
<td>Hemisphere, lens</td>
<td>Linear reciprocating (static weights)</td>
</tr>
<tr>
<td></td>
<td>0.64 (ventral forearm)</td>
<td>Glass</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Highley et al. (1977)</td>
<td>0.2-0.3</td>
<td>Nylon</td>
<td>Disc</td>
<td>Rotational (spring load)</td>
</tr>
<tr>
<td>Prall (1973)</td>
<td>0.4</td>
<td>Glass</td>
<td>Disc</td>
<td>Rotational (spring load)</td>
</tr>
</tbody>
</table>

Table 2-2: Reported values of CoF for untreated skin in vivo (reproduced from Sivamani et al., 2006)
<table>
<thead>
<tr>
<th>Study</th>
<th>Force (N)</th>
<th>Material</th>
<th>Size/Description</th>
<th>Apparatus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cua et al. (1990)</td>
<td>0.34 (forehead)</td>
<td>Teflon</td>
<td>15 mm diameter, disc</td>
<td>Rotational (spring load)</td>
</tr>
<tr>
<td></td>
<td>0.26 (ventral forearm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.21 (palm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.12 (abdomen)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.25 (upper back)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Johnson et al. (1993)</td>
<td>0.3-0.4</td>
<td>Glass</td>
<td>8 mm (radius of curvature) lens</td>
<td>Linear reciprocating (static weights)</td>
</tr>
<tr>
<td>Asserin et al. (2000)</td>
<td>0.7</td>
<td>Ruby</td>
<td>3 mm diameter sphere</td>
<td>Linear reciprocating (static weights)</td>
</tr>
<tr>
<td>Elsner et al. (1990)</td>
<td>0.48 (forearm)</td>
<td>Teflon</td>
<td>15 mm diameter disc</td>
<td>Rotational (spring load)</td>
</tr>
<tr>
<td></td>
<td>0.66 (vulva)</td>
<td>Teflon</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sivamani et al. (2003)</td>
<td>0.33-0.55</td>
<td>Stainless Steel</td>
<td>10 mm diameter sphere</td>
<td>Linear reciprocating (computer controlled load)</td>
</tr>
<tr>
<td></td>
<td>0.45-0.65</td>
<td>Stainless Steel</td>
<td>13 mm diameter cylinder</td>
<td>Linear reciprocating (computer controlled load)</td>
</tr>
<tr>
<td></td>
<td>0.81-1.17</td>
<td>Copper</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.19-1.71</td>
<td>Copper</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.25-1.81</td>
<td>Copper</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Egawa et al. (2002)</td>
<td>0.2-0.3</td>
<td>Piano Wire</td>
<td>100 mm square</td>
<td>Linear reciprocating (computer controlled load)</td>
</tr>
<tr>
<td>Zhang and Mak (1999)</td>
<td>0.40-0.62</td>
<td>Teflon</td>
<td>Annular ring</td>
<td>Rotational (spring balance)</td>
</tr>
<tr>
<td></td>
<td>0.37-0.61</td>
<td>Teflon</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Li et al. (2001)</td>
<td>2.48-3.25</td>
<td>Sandstone, Slate and Granite</td>
<td>125 x145 mm planar surface</td>
<td>Linear reciprocating (panellist controlled)</td>
</tr>
<tr>
<td></td>
<td>3.00 (no chalk on hands)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.47 (chalk on hands)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The great difficulty in measuring friction lies in controlling the condition of skin since humidity, among other variables, is known to affect skin friction. Further, the measurement instruments used also pose a problem as the normal load in many setups, especially in in vivo experiments, is hard to maintain at a constant level.

### 2.3.3 Proposed Mechanisms of Skin Friction

#### 2.3.3.1 Introduction

Skin friction (F) of a non-lubricated surface is generally attributed to two mechanisms. The first is the force required to overcome the adhesive force ($F_a$) between the two interacting surfaces. The second is due to deformation ($F_d$) which is composed of two parts, ploughing and hysteresis (see figure 2-12). These two components together are summed in the two-term non-interacting model of friction given by equation 2-2:

$$F = F_a + F_d \quad \text{Equation 2-2}$$
The magnitude of each term is highly dependent on factors such as the properties of the interacting materials, the normal load applied, sliding speed and environmental conditions. Adhesion friction ($F_a$) is considered to be the dominant mechanism for elastic and viscoelastic materials and the contribution of deformation friction ($F_d$) is considered negligible. For this reason, dry skin friction is said to be adequately explained by adhesion mechanisms.

2.3.3.2 Adhesion Friction

Adhesion friction can be attributed to two factors, the surface energies of the interacting surfaces (the nature of the adhesive bond) and the surface area over which the adhesive bonds are formed. Therefore, adhesion friction force is proportional to the shear strength ($\tau$) and the contact area ($A$):

$$F = \tau A \quad \text{Equation 2-3}$$

The area is defined using the Hertz contact model since skin is deformable:

$$A = \left(\frac{K W}{E}\right)^{2/3} \quad \text{Equation 2-4}$$

where $K$ is a collective term that includes the average dimension of the adhesive contacts and the number of adhesive contacts per unit area. $W$ is the applied load and $E$ is the Young's modulus of skin.

Combining equation 2-3 and 2-4 gives adhesion friction force and COF (equation 2-5 and 2-6, respectively):
Important observations can be drawn from the relationships defined in equations 2.4 to 2.6. Firstly, the surface area does not increase linearly with applied load but in a more gradual manner; this leads to the COF being inversely proportional to normal load to the power of one third. Further, the contact area is inversely dependent on the Young's modulus suggesting that softer materials result in larger contact areas than harder ones.

Koudine et al., 2000 carried out an experiment on the forearm using a glass half-sphere probe at a maximum normal load of 0.8 N and a sliding speeds of 0.125 mm s\(^{-1}\) and found experimentally that:

\[
\mu \propto \frac{F_t}{W} \propto \tau \left(\frac{K}{E}\right)^{\frac{2}{3}} W^{-\frac{1}{3}}
\]  
Equation 2-6

Figure 2-13 shows both static and dynamic friction, where equation 2-7 describes dynamic friction.

Sivamani et al., 2003 found a similar relationship (Eq 2.8) using a 10 mm diameter spherical stainless steel probe on the dorsal skin of the finger. A maximum normal load of 0.44 N (45 grams force) was applied at a sliding speeds of 5 mm min\(^{-1}\) (see figure 2-14).
This seems to indicate that skin does not obey Amontons’ laws and that the CoF is inversely proportional to normal load. The data from which these relationships were developed were from experiments carried out at normal loads under 1 N. The normal loads used in shaving on average range between 1 and 3 N and therefore, it is crucial to carry out experiments with normal loads in this higher range.

Adams et al., 2007 proposed that the interfacial shear strength term in equation 2-3 can be modelled using an equation (2-9) adopted from the shear properties of thin organic films (Briscoe et al., 1975), where:

\[ \tau = \tau_0 + \alpha \cdot p_r \]  

Equation 2-9

where \( \tau \) is the interfacial shear strength of skin, \( \tau_0 \) is the intrinsic shear strength, \( \gamma \) is the pressure coefficient and \( p_r \) is the real pressure (W/Ar), giving the following equation (2-10) for the coefficient of friction in terms of real pressure:

\[ \mu (p_r) = \frac{\tau Ar}{W} = \frac{\tau_0}{p_r} + \gamma \]  

Equation 2-10

The apparent and real contact areas and pressures are related by Eq 2-11:
The distinction between apparent and real contact area is primarily based on the assumption that all surfaces are rough at some length scale; therefore, the apparent contact area is generally higher than the real area of contact.

The coefficient of friction can be re-written in terms of apparent contact pressure \( p \) as follows:

\[
\mu (p) = \frac{A_r \tau_0}{A_p} + \gamma
\]

Equation 2-12

Derler et al., 2012 showed that most of the literature data in the dry and wet states fall within the area bounded by the curve determined by equation 2-12 and the axes, with the exception of data from PTFE which was not included (figure 2-15). The blue curve in figure 2-14 represents this maximum value of COF for a given normal load when the apparent and real areas of contact are equal. This is thought to occur for wet skin, where capillary bridges increase contact area.

![Figure 2-15: CoF as a function of apparent contact pressure assuming a pressure coefficient of \( \gamma = 0.8 \) interfacial shear strength of 13.3 kPa based on \( E = 3.6 \) where \( E = 40 \) kPa (red data points – dry skin and blue data points – wet skin) (taken from Derler et al, 2012)](image-url)
Literature data on the effect of sliding speed on skin friction is limited. Tang et al., 2008 showed that for a limited test range of 0.5-4 mm/s at a normal load of 0.2 N increasing sliding speed increases the COF.

Much of the data on skin friction has been modelled using the assumption that deformation friction contributions are negligible. Adams et al., 2007 and other researchers found deformation friction to contribute as little as 0.05 to the total COF, which is an order of magnitude less than adhesion friction. These results in the literature are based on very low normal loads (usually <1 N) and sliding speeds. The contribution of deformation friction is expected to increase with increasing normal load and/or where the surface is sufficiently lubricated such that the contribution of adhesion friction becomes insignificant. Given that deformation cannot be ruled out in shaving, it is considered in the next section.

### 2.3.3.3 Deformation Friction

Deformation friction of skin has been likened to that of soft elastomers which are viscoelastic. In these materials the bulk of the deformation friction is attributed to hysteresis loss, while the contribution of ploughing friction is considered negligible in comparison. Ploughing friction, as the name indicates, refers to the harder material of the two interacting materials, ploughing or wearing the softer material. The origin of hysteresis friction is hypothesised to be due to an asymmetric pressure distribution at the asperity contact resulting in a net force in plane. This is illustrated in figure 2-16, where two contact conditions are shown. The first case represents a sliding contact where the pressure distribution around the centre of the asperity contact is symmetrical; this means that the resultant force (friction) in the sliding direction is zero. The second case represents an asymmetrical pressure distribution around the centre of the asperity contact, resulting in a net friction force in the opposite direction to the direction of sliding (Moore et al., 1974). The asymmetry arises from the inherent ability of viscoelastic materials to stiffen under high deformation rates.
Figure 2-16: Schematic diagrams of the physical interpretation of hysteresis friction (p – pressure) (reproduced from Moore et al., 1974)

Figure 2-17 illustrates the effect of sliding speed on pressure distribution. At low sliding speeds, the contact radius is symmetrical about the centre of the asperity, giving a very low friction (point A in the inset of figure 2-17). As the sliding speed increases, the material stiffens and asymmetry ensues, increasing hysteresis friction (B). As the sliding speed is increased further, the material has less time to respond, stiffening further, this has the effect of returning the contact radius into near symmetry (C). An important observation is that, going from A to B then C in figure 2-17, asymmetry is assumed to cause deformation friction. Further, the material property (modulus) controls the asymmetry and ultimately friction i.e. hysteresis loss.
Pure rolling is a method used to measure hysteresis friction. Using elastomers, theoretical models have been developed by Greenwood et al., (1961) to estimate hysteresis friction for spherical and cylindrical probes.

The energy lost due to rolling is estimated by determining the total energy input and the proportion of this energy that is recovered per unit distance of rolling. The contact region is split into two, the front region which is in compression and the rear region which is in recovery since the roller is advancing forward. If no energy was lost in the system, there would be no friction. In reality, the recovery is incomplete and energy is expended in rolling over the surface. The ratio of lost energy to input energy is termed the hysteresis loss factor.

Equations 2-13 and 2-14 were derived by Greenwood et al., (1961) to estimate hysteresis friction for cylindrical and spherical rollers.

Equation 2-13

\[
\text{Cylinder: } F_c = \alpha \frac{2 W a}{3\pi R}
\]
Sphere: \[ F_s = \alpha \frac{3 \, Wa}{16 \, R} \]

where \( F_c \) and \( F_s \) are the cylindrical and spherical deformation friction, \( R \) is the probe radius (sphere/cylinder), \( a \) is the contact radius and \( \alpha \) is the hysteresis loss factor.

Johnson et al., (1993) using equation 2-14 estimated the coefficient of deformation friction to be 0.05 at a normal load of 0.2 N for skin. This was based on a spherical probe with a radius of 8 mm, hysteresis loss value of 0.24 (24%) and elastic modulus of 40 kPa. Similar results were obtained by Kwiatkowska et al., (2009) who found a coefficient of deformation friction between 0.04-0.05 at normal loads between 0.19-0.5 N. Further, Adams et al., (2007) measured rolling friction at sliding speeds ranging between 8 and 50 mm s\(^{-1}\) and showed rolling friction to contribute 0.04 to the total coefficient of friction at a normal load of 0.2 N on the forearm.

Many researchers neglect the contribution of deformation friction and concentrate on adhesion friction. The rates and normal loads applied in the vast majority of the studies reported in the literature data are relatively low. A typical shaver applies an average normal load in the range of 1-3 N and sliding speeds are as high 300 mm s\(^{-1}\), therefore, the contribution of deformation friction is hypothesised to increase for these higher normal loads and sliding speeds. The present work will address this apparent gap in the literature.

### 2.3.4 Effect of surface properties on skin friction

The topography of skin changes depending on the body region being considered e.g. concentric ridges on the finger pad and furrows on the forearm. Table 2-3 shows surface roughness values measured on various part of the body, where \( Ra \) values range from 11 to 26 \( \mu m \). The effect of surface roughness of skin on friction has not been studied extensively in the literature. Egawa el al., (2002) found no correlation (\( p = 0.230 \) where \( p<0.05 \) is considered significant) between skin roughness (\( Ra \)) and the coefficient of friction of the ventral forearm using linear regression (53 panellists). Nakajima et al., (1992) found that the coefficient of friction increased with density of primary lines. These two studies show potentially conflicting data and the true effect of roughness of skin on friction is unknown and requires further investigation.
The human skin is covered by an acidic hydro-lipid film with pH of 4-6. This hydro-lipid covers the stratum corneum as a water-oil emulsion and is composed of water and sebum from sweat and sebaceous glands, respectively. The influence of this hydro-lipid film has been shown to influence the adhesion properties of skin through capillary force. Pailler-Mattei et al., 2007 showed that the removal of the lipid film from skin resulted in reduced friction compared with normal skin. While, Cau et al., 1995 showed that for different skin regions, skin lipid film played a limited role in skin friction. Further fundamental work is required to establish the role of hydro-lipid film on skin friction.

Table 2-3: Surface roughness values for two persons aged 20 and 45 years (reproduced from Derler et al, 2012)

<table>
<thead>
<tr>
<th>Skin Region</th>
<th>Ra (µm) (range)</th>
<th>Rz (µm) (range)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Index finger</td>
<td>26.1 ± 6.1 (19-33)</td>
<td>87.3 ± 17.1 (62-99)</td>
</tr>
<tr>
<td>Edge of hand</td>
<td>14.9 ± 6.7 (9-22)</td>
<td>54.1 ± 21.2 (33-73)</td>
</tr>
<tr>
<td>Back of hand</td>
<td>(23-28)</td>
<td>(138-144)</td>
</tr>
<tr>
<td>Volar forearm</td>
<td>(17-20)</td>
<td>(119-125)</td>
</tr>
<tr>
<td>Volar forearm</td>
<td>(12-13)</td>
<td>(82-92)</td>
</tr>
<tr>
<td>Forehead (temple)</td>
<td>(12-15)</td>
<td>(84-95)</td>
</tr>
<tr>
<td>Cheek</td>
<td>(11-15)</td>
<td>(33-45)</td>
</tr>
</tbody>
</table>

2.3.5 Hydration

Hydration influences on the CoF are complex and are determined by the intrinsic state of skin e.g. anatomical site, age and extrinsic factors such as the humidity and other environmental exposures. Most researchers have carried out hydration work using two methods. The first method is the deliberate hydration of skin by exposing the skin region of interest to water for a given period of time and subsequently measuring the coefficient of friction. The second method involves modifying the humidity of the test environment to hydrate the skin. In both cases, water was not visible on the surface of the skin when measurements of friction were carried out. Early researchers, including Naylor et al., (1955), Comaish et al., (1971), Prall, (1973), El-Shimi, A. F. (1977), Highley et al., (1977), Nacht et al., (1981) and Wolfram, (1983) conclusively showed that hydration has a significant effect on skin friction. Their research showed that hydrated skin had as much

1 This is usually a subjective measure, where skin is pat dried before measurements are carried out
as seven times higher skin friction compared with normal skin\(^2\). More recent work by Sivamani et al., (2003) and Adams et al., (2007) has shown the transient effect of hydration, where the addition of water to the surface of skin is seen to increase the COF but this effect is limited to a few minutes as the skin dries and the COF returns to the value of dry skin. Figure 2-18 shows this behaviour of the COF in the presence of water.

An important part of understanding the effect of hydration is establishing levels of hydration. Dry skin is considered to be skin that is in equilibrium with the environment, while, hydrated skin is skin that has had water applied to it, to increase its water content and finally, wet skin is skin that has water film on its surface (water acting as a lubricant). Hydration studies have shown that drier skin has a lower CoF compared with hydrated skin. Further, very wet skin is seen to have a CoF similar to dry skin showing the complex behaviour of skin friction. The effect of increasing relative humidity (which influences hydration) is to increase skin friction. Hendriks et al., (2010) found that on the cheek and forearm increasing relative humidity from 37% to 92% resulted in skin friction that was twice as high as in a dry climate (36-37% relative humidity). The effect of hydration is to increase or decrease the real of contact. The increase in friction is attributed to the softening of skin which results in an increased contact surface area due adhesive forces.

---

\(^2\) The level of hydration is subjectively judged using terms such as dry, hydrated, moist and wet.
between water and the probe. This effect is known as water plasticization and occurs on
the stratum corneum, the outermost layer of skin (Adams et al., 2007).

2.3.6 Lubricants/Emollients/Moisturisers
Many cosmetic and skin researchers have investigated products and ingredients that
influence and achieve the appearance and feel of healthy skin. These studies primarily
focus on powders, oils, moisturisers and emollients. An important aspect of friction
testing is understanding the effect of lubricants. Lubrication is classed into four regimes
depending on the level of fluid present in the contact. Figure 2-19 illustrates the four
regimes of lubrication and the conditions under which they form are indicated on a
Stribeck curve. The Stribeck curve is a plot of the coefficient of friction as a function of the
Sommerfeld number; the Sommerfeld number is the product of viscosity (\( \eta \)) and sliding
speed (\( v \)) divided by the pressure (\( p \)).

Hydrodynamic lubrication is achieved when the two surfaces are separated by a thick
film of fluid. This fluid supports the load resulting in low coefficient of friction values
compared with some of the other lubrication regimes that will be discussed. The lubricant
thickness in this regime is greater than the summits of the asperities of the interface
making it the ideal lubrication regime in which to be.

Elastohydrodynamic lubrication is a subset of hydrodynamic lubrication which it is
induced by high contact pressure due to small contact area. The high contact pressures
modify the viscosity of the fluid as well as causing deformation of the contacting bodies.
Mixed lubrication is where two lubrication regimes, namely hydrodynamic and boundary
lubrication, are both present. In this regime, there are areas of contact where the film is
very thin and surface asperities are in contact alongside other areas where a lubrication
film separates the surfaces. The presence of the lubricant in the contact area prevents the
asperity contacts from developing strong adhesive contact, resulting in a lower friction
compared with boundary lubrication.

Boundary lubrication regime is achieved when the contact area is dominated by very thin
films at the monomolecular or multi-molecular level interacting with the surface
asperities across the whole contact area. Boundary lubrication is governed by the
properties of the interacting surfaces and their ability to adsorb lubricant (physical or
chemical adsorption) onto their surface. This leads to significant asperity contact leading to a high coefficient of friction compared with other lubrication regimes.

![Lubrication regimes diagram](image)

**Figure 2-19:** The lubrication regimes between interacting surfaces (h – film thickness, σ – standard deviation of the surface heights of the two surfaces, η – viscosity, v – sliding velocity and P – pressure). Film thickness for the four regimes (top), ratio of film thickness and standard deviation (middle) and coefficient of friction as a function of sommerfeld number (bottom) (Bhushan, B., 2013)

Water as a lubricant was investigated by Johnson *et al.*, (1993) using a glass probe on the forearm. The forearm was immersed in water for 120 seconds before wet measurements were carried out. Figure 2-20 shows the skin friction (dynamic/kinetic) as a function of velocity. Wet skin is seen to have a higher friction compared with dry skin even at relatively high sliding speed (50 mm/s). The presence of water in the contact area causes a stick and slip effect which is not seen for the dry contact (see figure 2-21).
Adams et al., (2007) carried out extensive research into the effect of water on skin friction. Two competing effects were proposed. The first is the reduction of the shear strength of the stratum corneum due to plasticisation and the second is a significant reduction in Young's modulus. Figure 2-22 shows the coefficient of friction as a function of time for a glass probe sliding on skin. The first section of the graph (termed hydration) shows the effect of adding water onto the surface of skin which gives an immediate increase in friction. Even though the shear strength of hydrated skin is lower than that of dry skin, wet friction remains higher than dry due to a significant reduction in Young’s modulus which translates to an increase in the real area of contact. The friction
contribution from an increase in contact area is greater than the reduction in shear strength; therefore, friction of hydrated skin is higher than dry skin.

The second phase of the graph (figure 2-22) shows the friction of drying skin, where a peak is seen in the friction curve. This is attributed to the loss of a boundary layer of water adsorbed onto the glass probe. This is in contrast to figure 2-18 which was done under similar conditions but with a polypropylene (PP) probe. It is suggested that the peak is not observed for the PP probe (figure 2-18) due to the poorer lubricity of water on PP (Adam et al., 2007).

![Figure 2-22: Coefficient of friction on skin using a glass probe with a radius of 8 mm. Sliding velocity of 8 mm/s and 0.5 N measured normal load (taken from Adams et al., 2007)](image)

Skin has a pH in the range of 4-6. Johnson et al., (1993) and Adams et al., (2007) have shown that sliding various materials after wetting with buffer solutions of increasing pH reduces the coefficient of friction of skin. This was attributed to the double layer repulsion effect due to charge polarity differences between the contacting surfaces and the solution. At pH values greater than the isoelectric point of skin (pH 5.5 on figure 2-23), the coefficient of friction of wet skin becomes similar to dry skin. Glass has an overall negative charge for the pH range covered in figure 2-23. For pH values lower than 5.5, a net attraction between the skin and the glass probe occurs, causing fluid film collapse, leading to high coefficient to friction values. While, for pH values greater than 5.5, the skin and glass become more negatively charged leading to greater surface repulsion hence a
thicker film forms between two the surface and ultimately a lower coefficient of friction is observed.

Figure 2-23: The coefficient of friction as a function of buffer solution pH for wet skin. Sliding velocity of 8 mm/s and normal load of 0.2 N. • glass probe, ■ ceramic probe and x sapphire probe. iep - Isoelectric potential of skin (taken from Adams et al., 2007)

Several researchers, namely Comaish et al., 1971, El-Shimi Naylor et al., 1955, Johnson et al., 1993 and Adams et al., 2007, have investigated the effect of various liquids on skin friction. Comaish et al., 1971 demonstrated that the application of various liquids including propylene glycol, silicone fluid and liquid paraffin as well as talc powder, significantly affected both static and dynamic coefficient of friction when compared with dry skin friction. The effect depended on the probe material used on skin where two categories of materials were investigated, knitted (wool, nylon and terylene) and sheet (P.T.F.E, nylon and polythene). The knitted materials showed an overall increase in friction compared with the sheet materials for the liquid lubricants investigated. For the solid lubricant i.e. talc powder, the effect of material was not clear (Comaish et al., 1971). Similarly, El-Shimi, 1977 showed that talcum powder reduced the coefficient of friction of skin by 50% and probe roughness had negligible effect in the presence of talcum powder. The reduction in coefficient of friction is attributed to the low shear strength of talcum powder. Further, the effect of probe roughness is negligible due to a transfer film of talcum powder onto the probe i.e. sliding occurs between talcum powder particles.

Johnson et al. (1993) and Adams et al. (2007) have carried out detailed work on the effect of silicone oil (a Newtonian fluid i.e. a fluid where the viscosity does not vary with shear
rate) on the coefficient of friction of skin. Figure 2-24 shows the coefficient of friction as a function of the product of viscosity and sliding speed for seven silicone fluids of varying viscosities. The product of viscosity and sliding speed was used instead of the Sommerfeld number because elastic modulus and normal load were kept constant in the experiment.

Figure 2-24: A Stribeck plot showing the coefficient of friction as a function of the product of viscosity and sliding speed. A glass probe (R = 0.008 m) was slid on skin with an applied normal load of 0.2 N and sliding speeds in the range of 1 to 50 mm/s. Silicone fluids with the following viscosities used: 0.8, 1.2, 110, 545, 970, 12190, and 58800 (+) mPa S. (taken from Adams et al., 2007)

For liquids with viscosities greater than water (η ~ 1 mPa S), the possibility exists for a lubricant film to separate the contacting surfaces at the converging region due to increased pressure (leading edge). This is termed isoviscous elastohydrodynamic lubrication since a soft substrate such as skin is involved. The term isoviscous is used to describe how the viscosity is unaffected by the relatively small pressures associated with ‘soft’ contacts, which is in contrast to ‘hard’ contacts (engineering materials) where increased viscosity is observed due to high pressures.

For small viscosities, figure 2-24 shows that the coefficient of friction of skin with silicone oil is relatively small and is comparable to the coefficient of friction of clean dry skin. This is characteristic of boundary lubrication. The small increase with velocity is due to the
velocity dependence of the interfacial shear strength. It is clear that silicone oil with greater viscosity is a more effective boundary lubricant. For higher values of viscosity and sliding speed ($\eta v$), isoviscous elastohydrodynamic lubrication (IEHL) is seen. The transition (minimum coefficient of friction in figure 2-24) between boundary and IEHL regimes is termed the mixed lubrication regime and is characterised by localised areas with hydrodynamic lubrication and others with boundary lubrication.

Nacht et al. (1981) investigated the effect of viscous lubricants (used in cosmetic products) on the coefficient of friction of skin over a period of hours. Three lubricants were investigated namely petrolatum, heavy mineral oil and glycerin. Figure 2-25 shows the coefficient of friction as a function of time of exposure. The results show that, compared with the baseline (dry skin), the coefficient of friction immediately reduces by as much as 25% before gradually increasing back to the baseline approximately an hour after exposure. The increased friction is maintained several hours after exposure. Two competing mechanisms are at work, the first involves the lubricating effect which results in an immediate reduction in friction but the second effect which these lubricants deliver is to reduce the rate of transepidermal water loss, which results in skin hydration. As was discussed in great detail above, hydrated skin has a higher coefficient of friction compared with ‘normal’ dry skin. Therefore, the effect of these lubricants is initially to decrease skin friction but with increasing time of exposure, the lubricants are absorbed into the skin and skin friction increases subsequently due to hydration. This is in contrast to the effect of water which only lasts for several minutes before it wears off.
2.3.7 Probes

The probes used to investigate skin friction in the literature have varied both in geometry and material as well as their mode of operation. This has made comparison across different experiments extremely difficult. This is further complicated by natural variations between subjects, test methodology and more importantly, controlling normal load in-vivo especially in sensitive areas such as the face. Two primary modes of probe operations are employed; rotational probes are designed to spin over the same test area, while linear probes move over new area as the stroke progresses. All these factors

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Figure 2-25: The effect of viscous lubricant on the coefficient to friction of skin (approx. 2 mg/cm² applied and each data point is a mean from five subjects) (reproduced from Nacht et al., (1981))
contribute significantly towards the variations reported for skin friction by many researchers.

Probe roughness has been reported to influence CoF (see data from El-Shimi, 1977 shown in table 2.2). Smoother probes gave higher CoF values compared with rougher probes of the same material (roughness values were not provided). This difference is attributed to the real area of contact increasing with smoother probes (Sivamani et al., 2006).

Hendriks et al., (2010) investigated the effect of probe roughness and hydration using a rotational probe on both the arm and cheek using two sets of probe materials (plastics and metals). The dry conditions were carried out in an environment with a relative humidity and temperature of 37% and 26° C, respectively. As for the humid conditions, the experiment was conducted in an environment with a relative humidity and temperature of 92% and 29° C, respectively. Figure 2-26 shows the coefficient of friction as a function of probe roughness for the two anatomical sites (arm and cheek). Probe roughness in the range 0.09 to 11.5 μm was investigated. The results show that increasing probe roughness for both dry and humid skin decreases the coefficient of friction. The coefficient of friction decreases on average by a factor of five going from a probe roughness of 0.1 to 11 μm (Hendriks et al., (2010)).

There are limited data on the effect of the physicochemical properties of probes on skin friction. Adams et al. (2007) showed, using hydrophilic (glass) and hydrophobic (polypropylene) probes on forearm skin, that the glass probe had a lower COF. Adams et al. (2007) argue that the coefficient of friction of skin is insensitive to surface energy due to the presence of water on the surface of skin causing plasticisation, even for normally dry skin. Therefore, for ‘hard’ probes contacting skin, the shear strength of the skin, which is significantly reduced by water, is more important than surface energy. Elkhyat et al. (2004) investigated the role of physicochemical property of probes on skin friction. Three probe materials were investigated namely PTFE (hydrophobic), steel (hydrophilic) and glass (hydrophilic). The results showed that pairing skin (hydrophobic) with a hydrophobic probe resulted in lowered friction compared with any other pair i.e. glass and steel (table 2-4). Hendriks et al. (2010) also investigated the role of probe material using hard plastics and metals. The results showed no difference between metals and plastics with the exception of PTFE. For example, aluminium had on average 25% lower
skin friction compared with PTFE (see figure 2-26 – the method used to fit data is unclear in the published article, however, the fitted lines are not ideal). The low friction of PTFE is attributed to its tendency to reorient its molecular chains to achieve low energy dissipation i.e. sliding friction (Pooley et al., 1972). Further work is required to fully understand the role of physicochemical properties on skin friction and forms part of the present work.

Table 2-4: Skin friction for different probe materials and their water contact angle

(Reproduced from Elkhyat et al., 2004)

<table>
<thead>
<tr>
<th>Sliding material</th>
<th>Coefficient of friction ($\mu$) of skin</th>
<th>Contact angle (surface energy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Teflon (PTFE)</td>
<td>0.12</td>
<td>113.7 ± 2.9</td>
</tr>
<tr>
<td>Steel</td>
<td>0.42</td>
<td>54.1 ± 2.3</td>
</tr>
<tr>
<td>Glass</td>
<td>0.72</td>
<td>42.4 ± 4.2</td>
</tr>
</tbody>
</table>

Figure 2-26: Coefficient of friction as a function of probe surface roughness ($a$ – data for the arm and $b$ – data for the cheek) ($\mu$m – micrometer $\mu$) (trend line fitting method unclear): Hendriks et al. (2010)
2.3.8 Anatomic site, age, gender and race

Several researchers have investigated the role of anatomical site, age, gender and race on the coefficient of friction. Gitis et al., (2004) investigated the coefficient of friction of the volar forearm and the results showed no significant difference across age, gender and ethnicity. The coefficient of friction varies with anatomical site, which different researchers have reported as shown in table 2-2. These variations are primarily attributed to differences in hydration across anatomical sites and environmental exposure (sun exposure) (Elsner et al., (1990), Zhang et al., (1999), Sivamani et al., (2003), Cua et al., (1990) and Cua et al., (1995)).

2.3.9 Key Skin Friction Trends

Derler et al., (2012) summarised graphically, as shown in table 2-5 the trends reported in the literature for key parameters of interest.

For some parameters, more than one relationship has been observed. For example, skin hydration, a linear relationship has been reported alongside a bell shaped relationship. The effect of hydration, as discussed in detail in section 2.3.5, involves different stages of hydration and drying, that occur during testing, especially when water is used a lubricant. Therefore, it is important to track the exposure time (time of application to time of measurement) to account for the different mechanisms that take place at different stages of hydration. Several trends have been reported for the effect of sebum, physiochemical properties of probes, surface roughness of probes and anatomical site on the coefficient of friction as shown in table 2-5. There is no significant effect of age and roughness of skin on the coefficient of friction.

The trends reported by many researchers collectively signify the care that needs to be taken when considering all the parameters affecting skin friction. Further, during testing it is important to remember the interdependence of various parameters in order to design experiments that give interpretable data. Thus, Table 2-5 gives an indication of the complexity involved with quantifying skin friction compared with traditional engineering materials which have well defined COF.
Table 2-5: Qualitative description of the trends reported in literature for skin friction (taken from Derler et al. (2012))

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Qualitative tendency of friction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skin hydration</td>
<td>![Graph] Increase or bell-shape</td>
</tr>
<tr>
<td>Sheen</td>
<td>![Graph] Constant or increase</td>
</tr>
<tr>
<td>Surface roughness of skin</td>
<td>![Graph] Constant</td>
</tr>
<tr>
<td>Hydrophilicity of contacting material</td>
<td>![Graph] Increase or decrease</td>
</tr>
<tr>
<td>Surface roughness of contacting material</td>
<td>![Graph] Decrease, increase or inverse bell-shape</td>
</tr>
<tr>
<td>Age</td>
<td>![Graph] Constant</td>
</tr>
<tr>
<td>Body region</td>
<td><em>(FH, PA) &gt; (VF, UB) &gt; DF &gt; (A, P) &gt; LB &gt; TH &gt; ABD</em> <em>F &gt; EH; VF &gt; CH; VU &gt; VF</em></td>
</tr>
</tbody>
</table>

FH forehead, PA postauricular, VF volar forearm, UB upper back, DF dorsal forearm, A ankle, P palm, LB lower back, TH thigh, ABD abdomen, F finger, EH edge of hand, CH cheek, VU vulva

2.4 Hair Cutting

2.4.1 Introduction

Hair cutting plays an important role in shaving but its contribution to the measured friction of a typical shaving stroke is unknown. The cutting behaviour of hair is of interest in shaving, while in the general literature the focus is primarily on the hair-hair friction, hair-chemical (e.g. shampoo and conditioner) interaction and the general feel or friction of hair in processes such as combing. This section will cover the basic structure and property of hair and the mechanisms controlling the hair cutting process.

2.4.2 Hair Structure

The structure of human hair is composed of three key concentric components: an innermost layer, the medulla (which might be present or not), a middle layer, the cortex and the outermost layer, the cuticle (figure 2-27). All these three elements are composed
of dead cells filled with keratin proteins, which account for 65-95 wt% (depending on the moisture content) and the remainder is water, lipids, pigment and trace elements (Bhushan, 2010).
hydrogen bonds between different chain molecules (figure 2-28). The content of cystine in hair has a significant impact on its physical and mechanical properties (Bhushan, 2010).

The cuticle is the outermost layer of hair and is commonly the most important since it interacts with the environment and chemical agents applied to hair. Cuticles cover hair from base to tip in overlapping layers (scales) similar to tiles on a roof (figure 2-29). This rough structure results in directional friction i.e. rubbing from tip to root has a higher friction compared with root to tip. Each cuticle is about 0.3-0.5 µm thick with a visible length of 5-10 µm. Human hair has 5-10 cuticles layers (Bhushan et al., 2010).

![Figure 2-29: Scanning electron micrograph of cuticle structure of beard hair (Thozhur et al., 2006)](image)

The cortex is composed of cortical cells and cell membrane complex. The cortical cells are 1-6 µm thick and 100 µm long, and run the length of the hair (longitudinally) and make up the majority of the inner fibre composition. The cell membrane complex is composed of cell membranes and adhesive material that bind cuticles and cortical cells together. The medulla is the inner most layer containing high lipids concentration and low cystine and makes up a small contribution to the total mass of hair with negligible effect on the mechanical properties of hair (Bhushan, 2010).

### 2.4.3 Properties of Human Hair

The general structure of human hair is consistent across different ethnic groups in terms of protein content and composition. The diameter of human hair varies from person to
person and for a given person as well as with age and ethnic group. Table 2-6 summarises the properties of human hair from three different ethnic groups. Figure 2-30 shows optical micrographs of beard hair for two subjects illustrating the inter and intra person variations associated with hair.

| Table 2-6: Variation in human hair diameter with ethnic group (taken from Bhushan, 2010) |
|--------------------------------------|-------------------|-------------------|---------------------|-----------------|
| Shape                      | Maximum diameter $(D_1)$ (µm) | Minimum diameter $(D_2)$ (µm) | Ratio $D_1/D_2$ | Number of cuticle scales |
| Caucasian Nearly oval       | 74                             | 47                             | 1.6               | 6–7              |
| Asian Nearly round          | 92                             | 71                             | 1.3               | 5–6              |
| African Oval-flat           | 89                             | 44                             | 2.0               | 6–7              |
| Average length of visible cuticle scale: about 5–10 µm |

Subject 1: Cheek
Subject 1: Chin
Subject 1: Neck

Subject 2: Cheek
Subject 2: Chin
Subject 2: Neck

Figure 2-30: Optical micrographs of beard hair from regions of the face for two subjects (taken from Thozhur et al., 2006)

Hair has high affinity to water due to its formation in an aqueous environment (forms beneath the skin) thus the keratinized structure achieves mechanical equilibrium prior to its emergence from the hair follicle. This equilibrium is maintained by the hair and
restored upon wetting (Wolfram, 2003). Wetting of hair leads to around 15% diametric swelling and around 1% change in length. This process is affected by humidity, temperature and chemical agents leading to a change in mechanical properties. Figure 2-31 shows the moisture uptake (regain) from zero to 100% humidity, further, the effect of chemical agents/processes on hair is shown in table 2-7. Therefore, the history of hair has a significant impact on its water content.

![Figure 2-31: Moisture absorption isotherm of human hair (taken from Wolfram, 2003)](image)

<table>
<thead>
<tr>
<th>Moisture regain (%) at</th>
<th>65% RH</th>
<th>95% RH</th>
<th>Liquid water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intact</td>
<td>15</td>
<td>32</td>
<td>34</td>
</tr>
<tr>
<td>Dyed</td>
<td>15</td>
<td>32</td>
<td>36</td>
</tr>
<tr>
<td>Bleached</td>
<td>16</td>
<td>35</td>
<td>50</td>
</tr>
<tr>
<td>Waved</td>
<td>15</td>
<td>33</td>
<td>41</td>
</tr>
<tr>
<td>Relaxed</td>
<td>15</td>
<td>34</td>
<td>57</td>
</tr>
</tbody>
</table>

Table 2-7: Moisture regain for different hair treatments (wt %) (taken from Wolfram, 2003)

Thozhur et al, (2006) carried out a detailed investigation into the effect of hydration on the modulus and yield strength of beard hair. Figure 2-32 shows, the results of tensile measurements carried out on beard hair in the form of curves of stress as a function of strain for dry and wet beard hair. The hair in the wet condition was soaked in water for 30 minutes. Strain rates of 5 mm/min were used for both dry and wet conditions. The effect of moisture was to reduce the Young’s modulus and yield strength by a factor of
three. Further, Young's modulus showed no dependence on the cross sectional area of hair (Thozhur et al., 2006).

Figure 2-32: Stress as a function of strain for beard hair carried at strain rate of 5 mm/min. (a)-Dry and (b)-wet (taken from Thozhur et al., 2006)

2.4.4 Hair cutting

Relevant to shaving is the contribution of hair cutting to total measured friction. There are limited data in the literature regarding the cutting of beard hair. The data available are based on in-vitro testing of extracted beard hair. This method of testing allows key variables of interest including hair diameter, hydration level, cutting speed etc, to be controlled. Early work by Deem et al, (1976) found that the cutting force of wet beard hair was 65% less than dry beard hair. Further, cutting force was seen to increase with cutting speed. These initial experiments did not consider the effect of blade angle and cross sectional area on cutting force i.e. cutting stress.

More recent work by Thozhur et al, (2007) investigated the role of cross sectional area on cutting force by considering the effect of hydration on cutting stress. Cutting stress is defined as the cutting force divided by the cross sectional area of the hair. Results showed that wet hair had 30% less cutting stress compared with dry hair, while blade angle and hair aging (relative to extraction time) had minimal effect on hair cutting stress. Several mechanisms of cutting were observed depending on the distance of the blade tip from the base of the hair.
Mechanism 1 is characterised by a sharp cut close to the base of the hair (less than two diameters of hair away) with a longitudinal split in the hair fibre. The blade initially penetrates the hair perpendicular to the hair axis then the blade proceeds towards the base of the hair, creating a longitudinal split before finally proceeding to cut the remaining hair radially (see figure 2-33).

Mechanism 2 involves stable penetration of the blade into the hair then bending and subsequently rapid fracture of the hair fibre. Similar to mechanism 1, this cutting mechanism occurs when the blade cuts close to the base of the hair (figure 2-34). It is unclear what controls the occurrence of mechanism 1 over mechanism 2.

Mechanism 3 occurs when the distance from the base of the hair to the contact point is greater than three hair diameters (between 4-6 hair diameters). The hair is more compliant leading to bending and sliding across the hair until the force is high enough to cause penetration. Then the blade proceeds at an angle leading to a skive cut instead of the cuts described above (figure 2-35).

If the distance between the base of the hair and contact point of the blade is further increased mechanism 4 is observed. This is characterised by further bending leading to skiving i.e. longitudinal cut that is more extreme compared with mechanism 3 (figure 2-36).
Figure 2-33: (a) Video images from an SEM cutting test showing failure mechanism 1. (b) SEM image of longitudinal split (taken from Thozhur et al., 2007).

Figure 2-34: (a) Video images from an SEM cutting test showing failure mechanism 2. (b) Fractured hair after cut (arrow shows direction of cut) (taken from Thozhur et al., 2007)
2.5 Concluding Remarks

The literature relating to the current understanding of skin friction and hair cutting has been discussed. Skin friction is a highly dynamic area of research and a core part of biotribology. To date, there is no standard model of skin friction. The system nature of friction coupled with the variable nature of skin results in the wide range of COF values quoted in literature, which range from 0.1 to 3. Parameters including normal load, sliding speed, humidity and temperature, probe material, probe geometry, test methodology,
anatomical site and individual to individual variation have all been shown to affect skin friction.

In light of the insights gained from the literature review, the broad aims of the project, as outlined in the introductory chapter, will be refined. Skin and hair cutting friction will be investigated separately, with the assumption that these two components are independent of each other. This approach allows fundamental work to be carried out before considering the interdependence of the two components. Further, two testing approaches will be adopted to investigate skin friction. The first testing approach is in-vivo testing on human subjects. This will be carried out to establish key parameters around which subsequent in-vitro testing will be developed. The in-vivo experiments have the following objectives:

- Normal load – skin friction does not follow Amontons’ laws and has an inverse relationship with normal load. However, the normal loads used in most of the literature studies have been < 1 N; this is significantly lower than the average load (1-3 N) measured for a typical shaver. Thus, one objective will be to investigate the relationship between load and the COF at loads relevant to shaving.

- Sliding speed – there are limited data on the effect of this parameter but it is expected to play a role due to the viscoelastic nature of skin. Sliding speed is difficult to control in-vivo; therefore attempts will be made to cover a range of sliding speeds with the objective of understanding its effects.

- Probe size and roughness – different probe sizes will be used to investigate the effect of apparent area of contact on skin friction. Differences in probe roughness may account for some of the variations reported for the COF of skin. Therefore, probes roughness will be controlled for all tests. The objective is to determine the effect of probe area, while minimising the effect of probe roughness.

- Probe material: literature data on the effect of probe material show conflicting relationships; it is not an objective of this part of the work to investigate probe material, so only one type of probe will be used.

- Anatomical site: the nature of the contact is expected to change between different anatomical sites due to the changing hydration and viscoelastic properties of different anatomical sites. For shaving, the face is the primary area of focus. To
gain insight into the effect of anatomical site on the coefficient of friction, the face will be split into two regions: fleshy and bony.

- Temperature and humidity: these parameters affect the living tissue primarily by changing the viscoelastic properties (skin plasticisation) and lubrication (sebum and sweat) of the skin. Therefore, the effect of environmental parameters such as humidity and temperature will be controlled or minimised to ensure consistent results.

*In-vitro* testing with the appropriate test substrate (skin mimic) opens up testing possibilities that would otherwise be unavailable *in-vivo*. The first is control over parameters of interest and the second is eliminating variations due to test subjects. However, to achieve this, a substrate that provides a consistent platform is required before key parameters can be investigated in a very controlled environment (discussed in chapter 3). Thus, a primary objective is to show that such a substrate is available.

A skin mimic is potentially the ideal platform to investigate the constituent components of skin friction namely adhesion and deformation friction and their relative contribution to total skin friction. This is an area that has received little attention in the biotribology literature. The objective of the *in-vitro* skin friction experiments is to verify the key relationships that will have been explored in the *in-vivo* experiments and further expand on these relationships. Further, it is expected that with the correct calibration of measurement instruments and the use of a suitable substrate, measurements will be more repeatable and reproducible compared with the *in-vivo* experiments. The focus will be on normal load, sliding speed, probe material and geometry (which will not be explored by the *in-vivo* experiments) and lubrication.

The capability is currently not available to isolate the contribution of hair cutting friction to total friction *in-vivo*. The limited data on hair cutting in the literature is based on single hair cutting carried out *in-vitro*. For this reason, a detailed investigation of hair cutting friction will not be carried out. Rather, the objective is to utilise *in-vitro* data of single hair cutting to develop a computer simulation model that will predict hair cutting friction in terms of hair density and type of hair cutting profile.

In order to fulfil one of the key aims of the project, which was to create a model that predicts shaving friction in terms of skin friction and hair cutting friction, *in-vitro* skin
friction and hair cutting data will be combined to form a model that predicts the relative contribution of skin friction and hair cutting friction to shaving friction. This will bring together the two components of shaving friction and thus indicate their relative importance in the shaving process.

The next chapter will discuss the materials and instruments that will be used to investigate skin friction both in *in-vivo* and *in-vitro*. The suitability of the skin mimic in terms of its mechanical and surface properties will be discussed in detail. Further, the probes and their properties as well as the friction measuring devices will be covered.
3 MATERIALS AND INSTRUMENTATION

3.1 Introduction
Having identified the need for both in-vivo and in-vitro testing, this chapter will present the details of the materials and instruments used for both sets of experiments. Firstly, the probe materials will be discussed, and then the skin mimic, which is relevant to the in-vitro experiments. Finally, the dynamic friction device (DFD) which is used in both sets of experiments is introduced as well as the Bladerunner which is used with the DFD in in-vitro testing. Repeatability and reproducibility are discussed in this section and they are defined as: repeatability is the closeness of agreement between independent results obtained with the same method on identical test material under the same condition, whereas, for reproducibility it is under a different condition.

3.2 Probes

3.2.1 Introduction
A typical cartridge (see figure 1-1) is composed of three key components/materials namely an elastomer, stainless steel blades and a lubrication strip. In investigating the key parameters of interest, simplified probe designs were used to gain a fundamental understanding of skin friction and its associated parameters.

Experiments carried out utilised two distinct set of probes, rectangular probes (mimicking the razor cartridge shape) and curved probes (spherical and cylindrical for comparison with literature). As discussed in the literature review, the effect of probe material is unclear at present with conflicting views on whether surface energy has a significant effect in determining friction. This was considered and contact angle measurements were carried out on the all probes used. Another important consideration is the relative hardness of the probes in relation to skin. All of the probes used had a much larger modulus than skin and therefore, deformation of the probes can be assumed to be negligible. Furthermore, all the probe materials used in these experiments are materials currently in Gillette razors and are therefore relevant to shaving.

3.2.2 Rectangular probes (in-vivo)
Three probe sizes were considered to investigate the effect of apparent contact area. One of the probe sizes is the same size as a typical Fusion cartridge dimension, while for the...
other two, one is larger and the other smaller than a Fusion cartridge (see table 3-1). The rectangular probes were made of stainless steel. The probes were made from thin sheets of stainless steel which were attached to a plastic base which then connects to the razor handle (see figure 3.1).

Roughness measurements were carried out using a stylus profilometer. Measurements were made at three different locations on each sample and the mean value taken (see table 3-1). Further, water contact angle measurements were carried out using the sessile drop technique. This involves placing a drop of water on the surface of the material and measuring the contact angle between the surface and the water droplet. An important consideration when measuring contact angle is to remove surface contaminants that might be present either from the environment or left from the machining of the probes. Several chemicals were used initially to determine their cleaning efficacy and ethanol was chosen for giving repeatable and reproducible measurements. Prior to all contact angle measurements, probes were swabbed with ethanol and cleaned with de-ionised water and allowed to dry in air. All measurements were carried out using de-ionised water with a drop volume of 8 μL.

Figure 3-1: A photograph of the stainless steel rectangular probes in three sizes to investigate the effect of nominal surface area.

Table 3-1: Specification for the stainless steel rectangular probes

<table>
<thead>
<tr>
<th>Probe Design</th>
<th>Material</th>
<th>Geometry (L X W)</th>
<th>Average Roughness (Ra)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectangular Cuboid</td>
<td>Stainless steel 440c</td>
<td>R1 - 3.8 cm x 1.0 cm</td>
<td>R1 – 0.55 ± 0.01 μm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>R2 - 3.8 cm x 1.5 cm</td>
<td>R2 – 0.57 ± 0.01 μm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>R3 - 3.8 cm x 2.0 cm</td>
<td>R3 – 0.52 ± 0.02 μm</td>
</tr>
</tbody>
</table>
### Table 3-2: Contact angle measurement carried out using de-ionised water

<table>
<thead>
<tr>
<th>Probes:</th>
<th>R1</th>
<th>R2</th>
<th>R3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact Angle (degrees)</td>
<td>Not available</td>
<td>88 ± 6</td>
<td>94 ± 3</td>
</tr>
</tbody>
</table>

### 3.2.3 Curved probes (*in-vitro*)

The curved probes were of two designs: cylindrical and spherical. Three materials were investigated, polytetrafluoroethylene (PTFE), Noryl and aluminium (figure 3-2). The probe design allowed two types of motion, rolling and sliding. This enabled deformation and adhesion friction to be separated (discussed in chapter 4).

![Figure 3-2: A photograph of the spherical and cylindrical probes (left Noryl, middle PTFE and right aluminium)](image)

The specification and contact angle measurement for each probe is given in tables 3-3 and 3-4, respectively. One further cylindrical probe was designed and made of stainless steel to be used as a reference probe for friction measurement carried out to determine the reproducibility and repeatability of the skin mimics (see section 3.3).

### Table 3-3: Specification for the curved probes

<table>
<thead>
<tr>
<th>Probe Design</th>
<th>Material</th>
<th>Size</th>
<th>Average Roughness (Ra)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sphere</td>
<td>1. Polytetrafluoroethylene (PTFE)</td>
<td>Diameter: 19 mm</td>
<td>1. 1.1 ± 0.05 μm</td>
</tr>
<tr>
<td></td>
<td>2. Noryl (polyphenylene oxide/polystyrene blend)</td>
<td></td>
<td>2. 0.45 ± 0.02 μm</td>
</tr>
<tr>
<td></td>
<td>3. Aluminium</td>
<td></td>
<td>3. 0.41 ± 0.04 μm</td>
</tr>
<tr>
<td>Cylinder</td>
<td>1. Polytetrafluoroethylene (PTFE)</td>
<td>Diameter:</td>
<td>1. 0.34 ± 0.2 μm</td>
</tr>
</tbody>
</table>
Table 3-4: Contact angle measurements using de-ionised water

<table>
<thead>
<tr>
<th>Probes:</th>
<th>PTFE</th>
<th>Noryl</th>
<th>Aluminium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact Angle (degrees)</td>
<td>98</td>
<td>77</td>
<td>64</td>
</tr>
</tbody>
</table>

3.3 Skin Mimic (*in-vitro*)

3.3.1 Introduction

The deformable skin mimic is a substrate that has been designed to reproduce the mechanical behaviour and surface texture of skin. This section of the thesis will show how well these properties are replicated by the skin mimic and more importantly, whether friction testing is repeatable and reproducible on this substrate. Other substrates exist which purport to mimic skin (e.g. Vitro-Skin) but these primarily focus on surface properties and do not mimic the bulk properties as well as surface, which the mimic discussed in this section does.

3.3.2 Skin mimic structure

The skin mimic is a multilayer substrate composed of 4 layers of varying thicknesses. The outermost layer is a water based polyurethane with a thickness of 50 µm, the second layer is composed of a polyurethane gel with a thickness of 2 mm, the third layer is made of silicone gel with a thickness of 7 mm and the base layer is made of silicone rubber with a thickness of 10 mm, giving a total thickness of ca 20 mm. Figure 3-3 shows a photograph of the skin mimic. This multilayer structure gives the skin mimic its non-linear viscoelastic behaviour. The surface texture of the skin mimic is based on a negative mould of skin. These combined properties result in a substrate that has significantly less variation in terms of its mechanical and surface properties compared with skin.
3.3.3 Mechanical behaviour

3.3.3.1 Stiffness

Stiffness is defined here in terms of the rate of change of normal load as a function of indentation depth. Figure 3-4 shows the force as a function of displacement for the skin mimic and different anatomical regions of the body (for more info see figure 2-8). The indentation test was carried out using an Instron mechanical testing machine for the forearm and skin mimic, while for the rest of the other body regions a bespoke instrument was used. The different regions of the skin were loaded to different end loads to reduce the risk of injury (sensitive body parts e.g. cheek socket).

Test areas were loaded between 0.3-2 N (2 N for the forearm and skin mimic) using a 1 mm diameter cylindrical steel probe at a rate of 3 mm/s. The panellists varied between 3-7 people (male and female) depending on the anatomical site tested and aged between 20 and 61 years old. The stiffness of the skin mimic falls within these regions of interest.
3.3.3.2 Hysteresis

Hysteresis energy is defined as the energy loss between the loading and unloading of the viscoelastic substrate. Figure 3-5 shows the percentage hysteresis loss for the skin mimic and the forearm. These measurements were carried out using an Instron mechanical testing machine. The test area was loaded to an end load of 1 N before unloading to zero normal load, at a rate of 3 mm/s (for more info see figure 2-9).
The skin mimic was not designed to mimic the forearm but overall, the two are comparable.

### 3.3.3.3 Stress relaxation
Stress relaxation is defined as the decay in stress as function of time. This phenomenon occurs for materials that display both elastic and viscous behaviours i.e. viscoelastic materials, where for a fixed strain, the applied stress reduces with time (flow of material under the test area, resulting in less reactive force). The percentage reduction in stress for a given duration of time is used as a measure of stress relaxation. Figure 3-6 shows the stress relaxation comparison between the forearm and the skin mimic.

The stress relaxation profile represented as percentage drop in the area under the curve for the skin mimic and the forearm are comparable (figure 3-6).

![Stress Relaxation](image)

**Figure 3-6**: Stress relaxation (% drop in area under the curve): 1 mm flat bottom cylindrical steel probe was used. 1 N normal load was applied at the start of the test (Skin Research, Gillette (2014)).

### 3.3.4 Surface properties

#### 3.3.4.1 Surface texture
The surface texture of the skin mimic is taken from the negative mould of skin. An image of the surface of the skin mimic taken using a 3D confocal microscope is shown in figure 3-7.
The surface of the skin mimic is characterised by rough peaks and troughs i.e. multi-scale roughness. Further, the average roughness value of skin and the average surface roughness of the skin mimic are comparable as shown in figure 3-8; hence the skin mimic is representative of the surface texture of skin.

Figure 3-8: A comparison between the surface roughness of skin mimic and skin (Darvin et al., 2008)
3.3.4.2 Contact angle

Water contact angle is used as an indicative measure of surface energy. Materials with low contact angles have higher surface energies (hydrophilic) and vice versa (hydrophobic). Figure 3-9 shows side by side images of sessile drops on the skin mimic (left) and skin (right), where both surfaces are hydrophobic i.e. contact angle greater than 90° (see figure 3-11).

Figure 3-9: Images of sessile drop on skin mimic (left) and skin (right)

![Contact angle > 90° Hydrophobic Surface](image)

![Contact angle < 90° Hydrophilic Surface](image)

![Contact angle (Degrees)](image)

Figure 3-10: Contact angle measurements of skin mimic and skin

The hydrophobicity of the skin mimic is illustrated well by the image in figure 3-11 from a 3D confocal microscope where it is clear that the area occupied by water is minimised. Figure 3-12 shows the same mimic with shaving preparation (Gillette Sensitive Gel),

![Table](image)
which is a surfactant (low surface energy liquid). The shaving preparation occupies a greater area on the skin mimic than water.

![Confocal image of water on the surface of the skin mimic](image)

**Figure 3-11: Confocal image of water on the surface of the skin mimic**

![Confocal image of shaving preparation (Gillette Sensitive Gel) on the surface of the skin mimic](image)

**Figure 3-12: Confocal image of shaving preparation (Gillette Sensitive Gel) on the surface of the skin mimic**

### 3.3.5 Dry friction of the skin mimic

#### 3.3.5.1 Introduction

To determine how repeatable and reproducible the friction data are from the skin mimic, several tests were carried out. These tests were done using a stainless steel cylindrical probe in sliding mode (see specifications in table 3.3). To test for repeatability, a set number of strokes were carried out and the friction force checked periodically. For reproducibility testing, friction was measured on five mimics from different batches. Surface roughness and water contact angle measurements were carried out to establish whether the surface of the skin mimic was affected by repeated stroking i.e. whether the surface was wearing.
3.3.5.2 Repeatability
A pristine skin mimic was stroked 750 times, and the friction values were recorded at the 1st, 250th, 550th and 750th strokes as shown in figure 3-13. A stroke is a single non-reciprocating sliding motion of a length of 150 mm. A normal load of 2.5 N and a sliding speed of 100 mm/s were used. The data shows that dry friction of the skin mimic is repeatable for a significant number of strokes.

![Repeatability of Dry Friction Data](image)

Figure 3-13: Dry friction data of the skin mimic using a stainless steel cylindrical probe: normal load of 2.5 N at a sliding speed of 100 mm/s (sliding length 150 mm)

3.3.5.3 Reproducibility
Five pristine skin mimics were tested and their dry friction measured. Each mimic was stroked at least three times at a normal load of 2.5 N and sliding speed of 100 mm/s. Figure 3-14 shows dry friction is reproducible across all five mimics.
Figure 3-14: Dry friction data of five skin mimics using a stainless steel cylindrical probe: Normal load of 2.5 N at a sliding speed of 100 mm/s (sliding length 150 mm)

3.3.5.4 Surface Roughness and Contact Angle

Average surface roughness and contact angle measurements were carried out pre and post stroking of the skin mimics to determine the effect of continuous stroking on the surface of the skin mimics (750 strokes). Figure 3-15 shows the average surface roughness pre and post stroke. There is no significant difference in roughness between the before and after stroked surfaces.

Contact angle measurements of the surface pre and post stroking are shown in figure 3-16. Similar to the average roughness data, there is no significant difference between before and after stroking. The before stroking reference value represents the average of the before stroking contact angle measurements averaged across all three mimics.
3.3.6 Conclusions Regarding the Skin Mimic

This section has shown that the skin mimic has mechanical and surface properties comparable to skin, in particular stiffness, hysteresis loss, stress relaxation, roughness and contact angle. Further, the skin mimic gives repeatable and reproducible friction results making it an ideal substrate for *in-vitro* testing.

3.4 Friction Measuring Devices

3.4.1 Introduction

This section will discuss the two primary instruments used to measure friction, namely the dynamic friction device (DFD) and the Bladerunner. Their properties, functionality,
calibration and validation are discussed in detail as they are important to the repeatability and reproducibility of friction measurements. The design of the instrument is not discussed due to confidentiality.

### 3.4.2 Components of the DFD

The dynamic friction device is designed to measure friction and normal load dynamically during a shaving stroke *in-vivo* and *in-vitro*. The design incorporates load cells in a razor handle to measure three forces, two in compression ($F_x$) and one in bending ($F_y$). The cartridge swivel angle is also measured using displacement sensors. The swivel angle and the three measured forces are combined to derive the normal load and friction force (see figure 3-17).

![Figure 3-17: Photographs of the DFD (left) and the forces measured on skin (right)](image)

#### 3.4.3 DFD Functionality

The DFD is based on strain gauge force sensors aligned so as to derive force in two planes. These are combined with displacement sensors used to determine the cartridge angle. The cartridge angle is used to resolve the forces onto two planes.
Figure 3-18 illustrates the coordinates by which the two measured forces $F_x$ and $F_y$ are defined relative to each other and relative to the derived parameters i.e. normal load and friction force, which is the same as $F_{\text{drag}}$; the two terms are used interchangeably throughout. The reference position is taken to be when the force $F_x$ is perpendicular to the face of the cartridge; this defines the 0 degree cartridge angle. The derivations of normal load and friction are given in appendix A.

![Diagram showing the forces relative to the cartridge](image)

**Figure 3-18 Diagram showing the forces relative to the cartridge**

### 3.4.4 Bladerunner

The Bladerunner system is composed of a robotic arm with a load cell that measures friction and a platform to hold the test substrates. The arm is positioned onto the substrate using a motor with a linear guide (figure 3-19).
The system also has a static load cell used to measure normal load prior to the commencement of a sliding stroke (‘balance’ in figure 3-19). Other features include a dipping tank for lubrication testing and interchangeable holder to cater for different substrates. Typical substrates include deformable and non-deformable skin mimics. Key system variables are sliding speed, normal load and sliding length. Table 3-5 summarises the range for each parameter.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Min Value</th>
<th>Max Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stroke Speed</td>
<td>1 mm s⁻¹</td>
<td>600 mm s⁻¹</td>
</tr>
<tr>
<td>Normal Load</td>
<td>Weight of the probe and support</td>
<td>19.6 N</td>
</tr>
<tr>
<td>Stroke length</td>
<td>1 mm</td>
<td>220 mm</td>
</tr>
</tbody>
</table>

### 3.4.5 DFD on Bladerunner

The DFD and Bladerunner can be combined to take advantage of their relative strengths. DFD friction measurements, especially when the swivel is fixed at zero degrees gives accurate friction data (see section 3.4.6) while the robotic arm and platform of the Bladerunner provide consistent normal load, sliding speed and stroke length, making the two systems ideal for *in-vitro* testing. Further, by using the skin mimic (discussed in section 3.3) in conjunction with the DFD and Bladerunner, greater control over the friction testing process is achieved. Figure 3-20 shows a typical test setup of the DFD and the skin mimic on the Bladerunner.
When the DFD on Bladerunner setup is used, friction data are taken from the DFD, while the normal load data are measured statically by the Bladerunner's load-cell. The normal load (load-cell) on the Bladerunner has an uncertainty of +/- 0.5%. Figure 3-21 shows the DFD on the load cell of Bladerunner.

3.4.6 DFD Calibration and Validation

DFD calibration involves two stages. The first stage calibrates the force sensors for loads up to and including ~7N. The second stage calibrates the displacement sensors for a swivel angle range of +/- 15 degrees. This implies normal loads and friction forces up to ~ 7N can be determined using the DFD.
The calibrated DFD is validated by testing across the calibrated range of loads (up to 7N) and swivel angle (+/- 15 deg). The loads measured in the positive and negative degrees are considered symmetrical, therefore only negative angles are considered in this discussion. The following combinations of loads and swivel angles were selected to determine the validity of the calibration across the range (table 3-6).

Table 3-6: Test conditions for validating the DFD

<table>
<thead>
<tr>
<th>Test Condition</th>
<th>0 degrees</th>
<th>-5 degrees</th>
<th>-10 degrees</th>
<th>-15 degrees</th>
</tr>
</thead>
<tbody>
<tr>
<td>~ 1N</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>~2N</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>~4N</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>~7N</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

The 16 combinations in table 3-6 were repeated 22 times to determine the mean and the standard error of each combination. Further, the percentage error between the expected value and the measured value was calculated to give an indication of the accuracy of the DFD.

Table 3-7 details the comparison between the expected values and the measured values for the combinations tested. The expected friction is zero since loads are applied statically (no sliding involved). The standard errors in the measured values are given in table 3-8.

Table 3-7: Summary of expected and mean measured values of normal load and friction for different cartridge angles

<table>
<thead>
<tr>
<th>Angle degrees</th>
<th>Expected Normal Load (N)</th>
<th>Measured Mean Normal Load (N)</th>
<th>Expected Friction (N)</th>
<th>Measured Mean Friction (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.0</td>
<td>0.992</td>
<td>0.0</td>
<td>0.007</td>
</tr>
<tr>
<td>0</td>
<td>2.0</td>
<td>1.940</td>
<td>0.0</td>
<td>0.001</td>
</tr>
<tr>
<td>0</td>
<td>3.9</td>
<td>3.812</td>
<td>0.0</td>
<td>0.010</td>
</tr>
<tr>
<td>0</td>
<td>6.9</td>
<td>6.626</td>
<td>0.0</td>
<td>0.222</td>
</tr>
<tr>
<td>-5</td>
<td>1.0</td>
<td>0.963</td>
<td>0.0</td>
<td>0.050</td>
</tr>
<tr>
<td>-5</td>
<td>2.0</td>
<td>1.986</td>
<td>0.0</td>
<td>0.049</td>
</tr>
<tr>
<td>-5</td>
<td>3.9</td>
<td>3.874</td>
<td>0.0</td>
<td>0.195</td>
</tr>
</tbody>
</table>

3—70 | P a g e
Table 3-8: The standard error on normal load and friction

<table>
<thead>
<tr>
<th>Applied Load</th>
<th>Swivel Angle</th>
<th>Standard Error Normal Load</th>
<th>Standard Error Friction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>0</td>
<td>0.003</td>
<td>0.002</td>
</tr>
<tr>
<td>2.0</td>
<td>0</td>
<td>0.003</td>
<td>0.003</td>
</tr>
<tr>
<td>3.9</td>
<td>0</td>
<td>0.003</td>
<td>0.001</td>
</tr>
<tr>
<td>6.9</td>
<td>0</td>
<td>0.005</td>
<td>0.003</td>
</tr>
<tr>
<td>1.0</td>
<td>-5</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>2.0</td>
<td>-5</td>
<td>0.005</td>
<td>0.005</td>
</tr>
<tr>
<td>3.9</td>
<td>-5</td>
<td>0.003</td>
<td>0.002</td>
</tr>
<tr>
<td>6.9</td>
<td>-5</td>
<td>0.006</td>
<td>0.005</td>
</tr>
<tr>
<td>1.0</td>
<td>-10</td>
<td>0.002</td>
<td>0.002</td>
</tr>
<tr>
<td>2.0</td>
<td>-10</td>
<td>0.003</td>
<td>0.003</td>
</tr>
<tr>
<td>3.9</td>
<td>-10</td>
<td>0.003</td>
<td>0.003</td>
</tr>
<tr>
<td>6.9</td>
<td>-10</td>
<td>0.003</td>
<td>0.002</td>
</tr>
<tr>
<td>1.0</td>
<td>-15</td>
<td>0.001</td>
<td>0.005</td>
</tr>
<tr>
<td>2.0</td>
<td>-15</td>
<td>0.003</td>
<td>0.005</td>
</tr>
<tr>
<td>3.9</td>
<td>-15</td>
<td>0.003</td>
<td>0.003</td>
</tr>
<tr>
<td>6.9</td>
<td>-15</td>
<td>0.007</td>
<td>0.005</td>
</tr>
</tbody>
</table>

Standard error is used to indicate the uncertainty around the mean; therefore a low value is indicative of a small uncertainty. The small standard errors in the measured means for both normal load and friction indicate that the mean values are close to the true mean.

The criteria used to determine a successful calibration are +/- 10% or less of the expected value for normal load and +/- 10% or less of the applied load for friction. The 10% level...
was based on an internal company standard. Table 3-9 summaries the percentage errors for normal load and friction for this particular DFD tested. This is an example of a DFD that passed the criteria set by the internal standard i.e. less than +/- 10%. From table 3-9, it is clear that the DFD is most accurate when the swivel angle is zero, especially at low normal loads. This is due to crosstalk (compression and bending channels affect each other) increasing at higher swivel angles and normal loads. *In-vitro* testing combining the DFD and the Bladerunner allow the swivel angle to be set to zero, taking advantage of this accuracy.

### Table 3-9: percentage error of normal load and drag

<table>
<thead>
<tr>
<th>Applied Load</th>
<th>Swivel Angle</th>
<th>Normal load Error %</th>
<th>Friction Error %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>0</td>
<td>1.2</td>
<td>0.7</td>
</tr>
<tr>
<td>2.0</td>
<td>0</td>
<td>-1.1</td>
<td>0.0</td>
</tr>
<tr>
<td>3.9</td>
<td>0</td>
<td>-2.8</td>
<td>0.2</td>
</tr>
<tr>
<td>6.9</td>
<td>0</td>
<td>-3.5</td>
<td>3.2</td>
</tr>
<tr>
<td>1.0</td>
<td>-5</td>
<td>-1.8</td>
<td>5.1</td>
</tr>
<tr>
<td>2.0</td>
<td>-5</td>
<td>1.3</td>
<td>2.5</td>
</tr>
<tr>
<td>3.9</td>
<td>-5</td>
<td>-1.2</td>
<td>5.0</td>
</tr>
<tr>
<td>6.9</td>
<td>-5</td>
<td>-3.5</td>
<td>8.9</td>
</tr>
<tr>
<td>1.0</td>
<td>-10</td>
<td>0.9</td>
<td>3.6</td>
</tr>
<tr>
<td>2.0</td>
<td>-10</td>
<td>-0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>3.9</td>
<td>-10</td>
<td>-1.1</td>
<td>3.7</td>
</tr>
<tr>
<td>6.9</td>
<td>-10</td>
<td>-2.6</td>
<td>5.5</td>
</tr>
<tr>
<td>1.0</td>
<td>-15</td>
<td>2.5</td>
<td>3.1</td>
</tr>
<tr>
<td>2.0</td>
<td>-15</td>
<td>-0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>3.9</td>
<td>-15</td>
<td>-0.5</td>
<td>2.1</td>
</tr>
<tr>
<td>6.9</td>
<td>-15</td>
<td>-1.2</td>
<td>3.6</td>
</tr>
</tbody>
</table>

### 3.4.7 DFD Stroke Analysis

The nature of skin friction testing means that stroke profiles i.e. normal load/friction as a function of time vary significantly and the average is typically taken to represent the dynamic friction. This is further complicated by the shaving process where typical stroke speeds are 100-300 mm/s, resulting in very short, almost spike-like responses.
Therefore, a method was developed to analyse these strokes and determine dynamic normal load and frictional forces.

The stroke profiles were analysed using a Matlab program which allows a subset to be taken from the region of interest. The subset is taken over a region in which friction (drag) is reasonably constant. The selection of this subset is done manually and hence is subjective. The corresponding normal load subset is taken as shown in figure 3-22. The CoF is then obtained by dividing the frictional (drag) force by normal load. When the DFD is combined with the Bladerunner, the friction subset is taken from the DFD and the normal load is taken from the Bladerunner load-cell.

Figure 3-22: Output from a typical stroke, showing how a subset of data is chosen.
3.5 Concluding Remarks

This chapter has covered the materials and instrumentation for both the in-vivo and in-vitro sets of experiments. For the in-vivo set of experiments, three rectangular probes were designed which have the same geometry as a Fusion cartridge. For the in-vitro set of experiments, curved probes made of three materials (PTFE, Noryl and aluminium) in two geometries (sphere and cylinder) were designed. The skin mimic was shown to replicate the viscoelastic response, surface roughness and water contact angle of skin. More crucially, friction measurements on the skin mimic are repeatable and reproducible for a significant number of strokes.

The DFD is an important friction testing device that measures normal load and friction both in-vivo and in-vitro. The Bladerunner is an in-vitro friction testing system that provides the platform and control over key variables such as normal load, sliding speed and stroke length. Combining the DFD and the Bladerunner systems improves the overall accuracy of normal load and friction measurements. The calibration and validation carried out has improved the overall friction testing capability and confidence in the friction results.

The next two chapters cover the in-vivo and in-vitro experiments that have utilised the DFD, Bladerunner and skin mimic to investigate skin friction. Chapter four presents the in-vivo experiments carried out to investigate the effect of normal load, nominal surface, probe size, anatomical site and skin state. Chapter five will cover the in-vitro experiments that investigated the relative contribution of adhesion and deformation friction to total friction.
4 IN-VIVO STUDIES: THE EFFECT OF NORMAL LOAD AND NOMINAL SURFACE AREA

4.1 Introduction

In-vivo testing is crucial for two key reasons, in order to establish key relationships between the COF and test variables: firstly, consistency with relationships established in the literature will be verified and this will give confidence in the testing system. Secondly, a range of test conditions relevant to shaving will be explored and in this way, relationships relevant to shaving will be established. Normal load and nominal surface area were identified as being key parameters influencing skin friction. Effects of anatomical site and skin state (dry and wet) will also be considered. Sliding speed, temperature and humidity will not be controlled but measured.

4.2 Overview of the Experiment

The aim of the experiment was to understand the effects of normal load, nominal surface area, anatomical site and skin state (hydration) on the CoF of skin. Table 4.1 lists the parameters that were varied (controlled) and those which were not.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Controlled/Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probe</td>
<td>Controlled – Three probe sizes</td>
</tr>
<tr>
<td>Normal load</td>
<td>Controlled – Three normal load levels</td>
</tr>
<tr>
<td>Anatomical site</td>
<td>Controlled – Bony and fleshy (cheek)</td>
</tr>
<tr>
<td>Skin state</td>
<td>Controlled – Dry and hydrated</td>
</tr>
<tr>
<td>Sliding speed</td>
<td>Not controlled but measured</td>
</tr>
<tr>
<td>Humidity and temperature</td>
<td>Not controlled but measured</td>
</tr>
</tbody>
</table>

The experiment was carried in-vivo on 20 panellists split into two groups. The test procedures for both groups were the same. All subjects shaved following a standard protocol prior to the test (see Appendix A.2).

4.3 Probes

Three rectangular probes were designed to test for the effect of nominal surface area on the CoF. The lengths of the probes were the same and the width was varied to achieve
three different surface areas (see figure 3-1). All the probes were made of the same material with similar surface finish (refer to table 3-1).

4.4 Normal Load
The aim was for a trained operator to achieve three distinct normal load values for a given condition (low, medium and high normal load). It is difficult to quantify prior to testing what low, medium and high normal load values should be due to variations in mechanical response of different subjects. Thus, the aim was to achieve three distinct normal load levels for each panellist.

4.5 Anatomical Site
The cheek was the anatomical site investigated in this experiment. The cheek was separated into two distinct areas as shown in figure 4.1. This is highly dependent on the panellist and what constitutes bony or fleshy is highly subjective and based on the operator.

![Figure 4-1: Photograph of the cheek separated into two distinct areas: bony and fleshy](image)

4.6 Skin State
All subjects shaved and acclimatised for a period of 1 hour prior to testing. The skin state refers to the lubrication state of the skin. This experiment considers two states, dry and lubricated (wet). Dry skin refers to skin in its natural state with no added lubricant after shaving the skin. The lubricated state refers to skin with a lubricant applied, in this case Gillette Series Shaving Gel Pure and Sensitive. This shave gel was chosen so that continual application would not irritate the skin, making it more comfortable for the subjects.
4.7 Stroke speed, Humidity and Temperature

Each stroke was recorded using a video camera and the video analysed to determine the average speed of each stroke. The humidity and temperature were measured using a humidity and temperature sensor. These parameters were not deliberately varied but their values were recorded. The measured range for RH% and temperature were 49.6 ± 8.9 % and 22.0 ± 2.0 °C, respectively.

4.8 Panellists

Panellists selected for this test were separated into two groups, each containing 10 members. The two groups were internal panellists (co-workers) and external panellists (recruited panellists). The panellist age ranged between 20 and 63 years old. The panellists consisted of 19 Caucasian males and one black male.

4.9 Randomisation of the Experimental Conditions

The controllable parameters determine the number of conditions executed per panellist. The dry and wet conditions were separated for logistical reasons and thus conducted on separate days for each panellist.

The conditions were randomised for each skin state i.e. dry and lubricated. A randomised list for a single panellist is shown in appendix A.3. For each panellist, 18 conditions for dry and 18 conditions for lubricated were conducted. Each condition was repeated three times resulting in 108 conditions in total per subject. The experimental protocol is shown in Appendix A.2.

4.10 Results

The coefficient of friction is plotted as a function of both normal load and pressure and is shown in figures 4-2 and 4-3 respectively. The figures represent data for all the conditions tested for all 20 panellists (dry and wet condition). Data are fitted using Excel, which utilises the least mean square method to achieve the best fit.
Figure 4-2: Coefficient of Friction as function of normal load. This graph contains all the data points collected from 20 panellists tested under different normal loads, nominal surface areas and hydration (with temperature, humidity and speed uncontrolled). W is normal load.

\[ \text{CoF} = 1.24W^{0.3} \]

Figure 4-3: Coefficient of Friction as function of pressure. This graph contains all the data points collected from 20 panellists tested under different normal loads, nominal surface areas and hydration (with temperature, humidity and sliding speed uncontrolled). Superimposed on the data are the best fit (blue) and maximum adhesion (green). P is pressure.

\[ \mu(p_r) = \frac{\tau A_r}{W} = \frac{\tau_0}{p_r} + \gamma \]

\[ \gamma = 0.8 \quad A_r = 1 \quad \tau_0 = 13.3 \text{ kPa} \]

\[ \text{CoF} = 1.42p^{-0.28} \]
The best fit line for the COF as a function of normal load (figure 4-2) shows the characteristic inverse relationship to the power of -1/3 measured by other researchers (Sivamani et al (2006) Koudine et al (2000)). The normal load range measured extends beyond those by other researchers and indicates that the COF does not follow Amontons’ law (CoF is inversely proportional to normal load to the power of 1).

The coefficient of friction plotted as a function of pressure is shown in figure 4-3 with the adhesion friction prediction superimposed on the data (see section 2-3-3-2 for details in particular figure 2-15). All the data points fall within the maximum predicted adhesion friction based on equation 2-11. This is fortuitous however, since adhesion friction is not the only parameter affecting skin friction especially at the higher normal loads, where deformation friction will contribute.

Figure 4-4 and 4-5 show the data for the dry state. Figure 4-4 shows the coefficient of friction as a function of normal load. The COF is inversely proportional to normal load but the power index is greater than -1/3, predicted and measured by other researchers. Further, plotting the coefficient of friction as a function of pressure in figure 4-5, the data points measured show scatter over a wide area but fall within the limits predicted theoretically to be the maximum adhesion friction (see section 2-3-3-2 for details in particular figure 2-15).
Figure 4-4: Coefficient of Friction as function of normal load for dry skin. This graph contains all the data points collected from 20 panellists tested under different normal loads and nominal surface areas (with temperature, humidity and speed uncontrolled). \( W \) is normal load.

\[
\text{CoF} = 1.48W^{-0.15}
\]

Figure 4-5: Coefficient of Friction as function of pressure for dry skin. This graph contains all the data points collected from 20 panellists tested under different normal loads and nominal surface areas (with temperature, humidity and speed uncontrolled). Superimposed on the data are the best fit (blue) and maximum adhesion (green). \( P \) is pressure.

\[
\mu (p_r) = \frac{\tau_r A_r}{W} = \frac{\tau_0}{p_r} + \gamma
\]

\[
\gamma = 0.8, \quad A_r = 1, \quad \tau_0 = 13.3 \text{ kPa}
\]

\[
\text{COF} = 1.54P^{-0.12}
\]
Data for wet skin is shown in Figures 4-6 and 4-7. Figure 4-6 shows coefficient of friction of wet skin (lubricated) closely matches the predicted index of $-1/3$. Further, plotting the COF as a function of pressure, it is clear that all the data points fall significantly below the predicted maximum adhesion friction (figure 4-7).

Figure 4-6: Coefficient of Friction as a function of normal load for wet skin. This graph contains all the data points collected from 20 panellists tested under different normal loads and nominal surface areas (with temperature, humidity and speed uncontrolled). W is normal load.
Figure 4.7: Coefficient of Friction as function of pressure for wet skin. This graph contains all the data points collected from 20 panellists tested under different normal loads and nominal surface areas (with temperature, humidity and sliding speed uncontrolled). Superimposed on the data are the best fit (blue) and maximum adhesion (green). P is pressure.

Figure 4-8 shows the coefficient of friction as a function of sliding speed for all 20 panellists. This seems to indicate an inverse relationship between the coefficient of friction and sliding speed. Since, this figure contains both dry and wet data, separating these two data sets will give a clearer indication of the relationship between the COF and sliding speed for each respective lubrication state. Figure 4-9 and 4-10 show that, the effect of sliding speed in this convoluted dataset is unclear and overall appears to be independent of sliding speed for both dry and wet skin. A dependence of friction on sliding speed is expected due to the viscoelastic nature of skin (and also the presence of a lubricant for the wet case) but it appears the variations in other parameters mask this effect.
Figure 4-8: Coefficient of Friction as a function of sliding speed. This graph contains all the data points collected from 20 panellists tested under different normal loads, nominal surface areas and hydration (with temperature, humidity and sliding speed uncontrolled).

Figure 4-9: Coefficient of Friction as a function of sliding speed for dry skin. This graph contains all the data points collected from 20 panellists tested under different normal loads and nominal surface areas (with temperature, humidity and sliding speed uncontrolled).
Figure 4-10: Coefficient of Friction as a function of sliding speed for wet skin. This graph contains all the data points collected from 20 panellists tested under different normal loads and nominal surface areas (with temperature, humidity and sliding speed uncontrolled).

The nominal surface area is a discrete parameter and therefore a box plot has been used to illustrate its effect on the COF as shown in figures 4-11 and 4-12. The box plot graphically illustrates data points in terms of a box where the centre is the median data point (50 % of the data), the lower section is 25% of the data and the upper section is 75% of the data. The range in the box is termed the inter quartile range. The vertical line extending from the box on either side signifies the maximum and minimum data points when there are no outliers or 1.5 times the inter quartile range. Data points above/below the vertical end of the line are outliers or suspected outliers.

The box plot for dry skin shows a greater spread compared with that of lubricated skin. This indicates the overall effect of different factors will be more pronounced in the dry case compared with the lubricated case, where the lubricant seems to normalise the surface of skin. Further, the average coefficient of friction increases with a decrease in nominal surface for the dry case, while for the wet case, nominal surface area has no effect on the mean COF (see figures 4-11 and 4-12, respectively).
4.11 Discussion

Data relating to the coefficient of friction as a function of normal load, sliding speed and nominal surface area in both dry and wet conditions were shown in figures 4-2 to 4-12. These figures collectively illustrate the difficulty associated with isolating the effect of a given parameter on the coefficient of friction in the presence of other varying parameters.
Whilst these figures represent a dataset composed of 20 panellists, there is a consistent trend that shows the CoF is inversely proportional to normal load for normal loads greater than 1 N, confirming literature data that showed that skin does not follow Amontons’ law. Further, the box plots show that increasing probe nominal area decreases skin friction. This is hypothesised to be due to the higher pressure produced by the smaller probes (for a given normal load), which increase deformation friction. Figure 4-13 illustrates this hypothesis.

Figure 4-13: The effect of probe size: increasing skin bulge leading to greater deformation friction

In order to make sense of the relationships between the various parameters, statistical modelling was undertaken to establish the significance of each parameter. The statistical hypothesis used stipulates that the parameters considered have no effect on the coefficient of friction. Therefore, if the probability is low, this indicates the parameter has an effect. A probability value (p-value) less than 0.05 is considered significant. A surface response model was used. This model involves separating parameters into two categories namely, random effects and fixed effects. For the set of parameters considered in this study, panellists were modelled as random effects and the remaining set of parameters as fixed effects. The fixed effects were normal load, probe size sliding speed, anatomical site, temperature and relative humidity. The next step was to create a list of single terms, squared terms and product terms of all six parameters. Then, the next step is to look at
the significance of each term on the COF. The significant terms on the list (p-value <0.05) are considered in the model, while, the remaining terms are discarded.

As stated earlier, the data analysed were taken from 20 panellists, 10 panellists were recruited from Gillette employees (internal) and the other 10 panellists were recruited from the public population. Data analysis carried out showed that these two groups of panellists had different relationships and for this reason, the statistical analysis was carried out separately for each group. Further, dry and wet data were different and as a result were also analysed separately.

Table 4-2 and 4-3 show the parameters found to be significant for dry skin. The data for the internal panellists (table 4-2) show that normal load, anatomical site, probe size and relative humidity are significant i.e. p value less 0.05. Some parameters were found to be significant as an interaction (product of two variables); in this case, sliding speed and normal load were highly significant (p <<0.05) as an interaction. For the external panellists, probe size, anatomical site, relative humidity and the interaction between temperature and normal load were found to be statistically significant.

**Table 4-2: Analysed parameters and their statistical significance for internal panellists on dry skin**

<table>
<thead>
<tr>
<th>Parameter: Dry Skin: Internal Panellists</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anatomical Site</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Probe size</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>%RH</td>
<td>0.0029</td>
</tr>
<tr>
<td>Sliding Speed</td>
<td>0.0302</td>
</tr>
<tr>
<td>log normal load (N)</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Probe size*ln normal load (N)</td>
<td>0.0208</td>
</tr>
<tr>
<td>Sliding Speed*log normal load (N)</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

**Table 4-3: Analysed parameters and their statistical significance for external panellists on dry skin**

<table>
<thead>
<tr>
<th>Parameter: Dry Skin: External Panellists</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probe size</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Anatomical Site</td>
<td>0.0001</td>
</tr>
<tr>
<td>%RH</td>
<td>0.001</td>
</tr>
<tr>
<td>Temp C</td>
<td>0.5504</td>
</tr>
<tr>
<td>Log Normal load (N)</td>
<td>0.6701</td>
</tr>
<tr>
<td>Temp (C) * Log Normal load (N)</td>
<td>0.0031</td>
</tr>
<tr>
<td>Probe size*Anatomical Site</td>
<td>0.0942</td>
</tr>
</tbody>
</table>
Tables 4-4 and 4-5 show the parameters that are statistically significant for the wet skin. For the internal panellists, anatomical sites, normal load, anatomical site interacting with relative humidity and sliding speed are statistically significant (table 4-4). For the external panellists, anatomical site, normal load, probe size and the interaction between anatomical site and temperature (table 4-5) are statistically significant. Again, some interactions that are statistically significant are difficult to explain, e.g. anatomical site and temperature interacting, while this might be plausible on dry skin (temperature might affect the mechanical properties of skin), on wet skin, small changes in temperature should not cause significant changes in COF.

Table 4-4: Parameters analysed and their statistical significance for wet skin Internal Panellists (parameter in red are significant)

<table>
<thead>
<tr>
<th>Parameter: Wet Skin: Internal Panellists</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anatomical Site</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>%RH</td>
<td>0.267</td>
</tr>
<tr>
<td>Sliding Speed</td>
<td>0.4441</td>
</tr>
<tr>
<td>log Normal load</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Anatomical Site*%RH</td>
<td>0.0343</td>
</tr>
<tr>
<td>Anatomical Site* Sliding Speed</td>
<td>&lt;.0001</td>
</tr>
</tbody>
</table>

Table 4-5: Parameters analysed and their statistical significance for wet skin External Panellists

<table>
<thead>
<tr>
<th>Parameter: Wet Skin: External Panellists</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anatomical Site</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Mean(Temp C)</td>
<td>0.558</td>
</tr>
<tr>
<td>Log Normal Load</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Anatomical Site*Mean(Temp C)</td>
<td>0.039</td>
</tr>
<tr>
<td>Probe size</td>
<td>&lt;.0001</td>
</tr>
</tbody>
</table>

These interactions demonstrate an important limitation with statistical analysis i.e. the potential for artificial interaction of independent parameters. For example, in table 4-2, normal load and sliding speed interact and this interaction is seen to be significant. This is problematic because, both of these variables should be independent. This interaction could actually be due to the behaviour of the operator running the experiment, who might stroke slowly when applying heavier loads and vice versa. Similar interactions are seen
in tables 4-3 and 4-5, for example, between temperature and normal load. Thus, using statistical analysis on a limited dataset with many variables, some of which are not controlled, leads to interactions that are difficult to interpret and in some instances seem implausible.

The significant parameters from tables 4-2 to 4-5 were used to develop four models that predict COF. Figures 4-14 to 4-17 show screenshots of the four models developed for internal and external panellists for both dry and wet conditions.

Figure 4-14: Influence of various parameters on the coefficient of friction according to the statistical model for dry skin for internal panellists (probe surface area are also referred to as A, B and C, where A is the lowest surface area of 3.8 cm²)
Figure 4.15: Influence of various parameters on the coefficient of friction according to the Statistical model for dry skin for external panellists.

Figure 4.16: Influence of various parameters on the coefficient of friction according to the Statistical model for wet skin for internal panellist.
While some plausible effects seem to have been captured by the models, they nonetheless highlight the complexity associated with *in-vivo* testing even with a carefully conducted experiment like this one. It is clear that some of the interactions observed are not plausible and this is attributed to the limited data set and the variable nature of skin. However, these models provide very important insights about some of the parameters investigated. Three of the models show that the COF is inversely proportional to normal load in line with literature data. Further, normal load has the biggest overall effect on the COF. Anatomical site has an effect in all four models, where, the COF is higher on the fleshy area of the cheek compared with the bony area of the cheek. Probe size (nominal surface area) and sliding speed seem to be important in some of the models but their overall effect is unclear. The measured range in relative humidity and temperature were very limited (in the test environment) and for this reason, their effect on COF is considered to be artificial.

### 4.12 Concluding Remarks

The normal load and nominal surface area experiment showed that normal load is the primary parameter having the largest effect on skin friction. The models developed illustrated the complexity associated with quantifying parameters affecting skin friction. Further, data based on many parameters some controlled and others not, carried out *in-vivo* and compounded with subject variations; lead to models that are complicated to...
interpret and contradictory in some cases. Nonetheless, this in-vivo experiment focused the scope of the in-vitro experiments that followed.

The next chapter will present a set of experiments carried out, focused by the conclusion from the in-vivo experiments investigating the effect of normal load, probe material, sliding speed and lubrication on adhesion and deformation friction which constitute the total measured skin friction.
5 IN-VITRO STUDIES: ROLLING AND SLIDING - SEPARATING ADHESION AND DEFORMATION FRICTION

5.1 Introduction

Skin friction testing *in-vivo* is expensive, time consuming and as discussed in section 4-10 and 4-11 fraught with difficulty especially in interpreting the results and establishing meaningful relationships. For this reason, *in-vitro* capability was developed. An important element of this *in-vitro* test capability is the skin mimic (discussed in section 3.3) which is a repeatable and reproducible test substrate. Other test variables can also be controlled more precisely.

Friction is generally attributed to adhesion and deformation friction and this set of experiments set out to separate these two components to establish their relative contribution to total skin friction using the rolling and sliding method. This is an important relationship to understand for two reasons: firstly, by understanding the relative contribution of each component and the parameters affecting this relationship, friction can be controlled to a desired end. Secondly, literature data in this area are limited and the results from this set of experiments will aim to fill that void.

Deformation friction is generally assumed to be negligible hence adhesion friction is wholly attributed to skin friction. The range of sliding speeds and normal loads investigated in the literature are limited and for this reason, these sets of experiments will aim to cover a wider range applicable to shaving. This experiment tests the hypothesis that deformation friction contributes a significant proportion to total friction especially for lubricated contacts. Further, the hypothesis proposed in section 4-10, which was that deformation friction increases with pressure, will also be investigated.

Five key parameters were investigated: normal load, sliding speed, probe material, probe geometry and lubrication. These parameters were chosen based on the *in-vivo* experiment discussed in chapter four as well as considerations based on the limited understanding of the role of probe material and geometry which are relevant for shaving.
5.2 Experimental Details

5.2.1 Methodology

To calculate adhesion and deformation friction, it has been assumed that rolling friction is due to deformation friction and that sliding is a combination of deformation friction and adhesion friction. Therefore, friction (F) is given by the two term non-interacting model of friction:

\[ F = F_{\text{adh}} + F_{\text{def}} \quad \text{Equation 5-1} \]

where \( F \) is friction, \( F_{\text{adh}} \) is the adhesion friction, \( F_{\text{def}} \) is the deformation friction.

Deformation friction (hysteresis friction) is measured using rolling friction, taking the friction contribution of the bearings in the roller into account:

\[ F_{\text{Rolling}} = F_{\text{def}} + F_{\text{Bearing}} \quad \text{Equation 5-2} \]

Sliding friction contains both deformation and adhesion friction i.e. equation 5-1 and 5-3 are equivalent.

\[ F_{\text{Sliding}} = F \quad \text{Equation 5-3} \]

For the purpose of separating adhesion and deformation friction, the friction contribution due to the bearings in the rollers were measured by rolling on a stainless steel substrate for all the test conditions. Thus, the calculated values of deformation and adhesion friction are given, respectively, by:

\[ F_{\text{Def}} = F_{\text{Rolling}} - F_{\text{Bearing}} \quad \text{Equation 5-4} \]
\[ F_{\text{Adh}} = F_{\text{Sliding}} - F_{\text{Def}} \quad \text{Equation 5-5} \]

Therefore, values for deformation and adhesion friction will be calculated from the rolling and sliding experiments.

5.2.2 Parameters/Variables

Table 5-1 summarises the properties and test setup of the experimental parameters. The properties of the probes investigated were shown in table 3-3 and a photograph of the probes in figure 3-2. A range was chosen for normal load and sliding speed that is relevant to shaving. Three lubrication conditions were considered termed dry, water and oil. To minimise cross contamination (wear) for the dry conditions between the three sets of
probes, testing was carried out in the order, aluminium, Noryl and then PTFE. The probes were switched between rolling and sliding modes using a shaft that was inserted across the length of the probes. When this shaft was inserted, it prevented the probes from rolling, giving sliding. Removing this shaft allowed the probes to roll freely (see figure 3-2).

**Table 5-1: Properties of the parameters investigated and test setup**

<table>
<thead>
<tr>
<th>Test Conditions</th>
<th>Property</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal load:</td>
<td>Sphere: Low ~ 0.7 N; Medium ~ 1.1 N; High ~ 1.3 N</td>
</tr>
<tr>
<td></td>
<td>Cylinder: Low ~ 1.1 N; Medium ~ 2.2 N; High ~ 2.8 N</td>
</tr>
<tr>
<td>Sliding Speed:</td>
<td>10, 50, 100, 200, 250, 300 (mm/s)</td>
</tr>
<tr>
<td>Probe Material:</td>
<td>Noryl (polyphenylene oxide/polystyrene blend), PTFE and aluminium</td>
</tr>
<tr>
<td>Lubrication:</td>
<td>Dry, water and shaving oil (Newtonian oil: Viscosity 0.3 Pa.s)</td>
</tr>
<tr>
<td>Stroke Length:</td>
<td>150 mm</td>
</tr>
<tr>
<td>Environment:</td>
<td>35-50% Relative Humidity and room temperature (20-24°C)</td>
</tr>
</tbody>
</table>

**5.2.3 Test Combination**

Table 5-2 summarises the test combinations that were carried out, a total of 648 experiments. Each experimental combination was repeated 3 times, giving a total of 1944 strokes. A single skin mimic was used for the whole experiment; this was possible because of the durability, repeatability and reproducibility of the substrate (see chapter 3, section 3-3-5). The dry combinations were carried out first, and then water and finally oil (see Appendix B.1 for an example of a complete test combination). The application of water and oil on the surface of the skin mimic was carried out manually, where the liquid was added and spread evenly across the surface before each stroke commenced.
5.2.4 Data Analysis

Each stroke measured was analysed using the method discussed in section 3.4.7. The DFD used for this experiment was modified to measure friction in both rolling and sliding motions. This particular DFD was more accurate compared with the standard DFD described in section 3.4.6. The uncertainty around the two measured parameters, i.e. normal load and friction, are shown in table 5-3. The data presented in section 5.3 do not include error bars due to the small values of uncertainties involved (they will not be visible relative to the data points).

Table 5-3: The uncertainty for normal load and friction measurements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal load</td>
<td>+/- 0.5 %</td>
</tr>
<tr>
<td>Friction</td>
<td>+/- 1.0 %</td>
</tr>
</tbody>
</table>

5.3 Results/Discussion

5.3.1 Introduction

Data in this section of the thesis are presented in several formats to focus on key relationships. Sections 5.3.2, 5.3.3 and 5.3.4 present relationships of skin friction as a function of sliding speed for bearing friction, deformation friction and adhesion friction.
in the dry contact case. These sets of data involve contacts with no lubrication. Also, the effect of sliding speed and normal load are more apparent when the data are plotted in this way. Sections 5.3.5 and 5.3.6 (adhesion friction of water contact and adhesion friction of oil contact respectively) show data using a Stribeck curve where the coefficient of friction (COF) as a function of the Stribeck number is plotted. These sets of data involve lubricants and this format of data presentation is effective in demonstrating the overall effect of sliding speed, normal load, viscosity and lubrication regime. Sections 5.3.7, 5.3.8 and 5.3.9 show plots of percentage contribution of adhesion and deformation friction to total friction as a function of sliding speed. The plots show the effect of normal load, sliding speed, probe material, probe geometry and lubrication and provide a comprehensive view of the effect of each parameter relative to the other.

5.3.2 Bearing Friction

Bearing friction was measured by rolling the test probes on a smooth stainless steel substrate. In order to account for all the test conditions, the same range of normal loads and sliding speeds were used. Initial testing showed negligible effect of probe material on rolling friction, therefore, PTFE was used as the reference probe to estimate the contribution of bearing friction. Figures 5-1 and 5-2 show the measured friction for the two probe geometries. The purpose of these measurements was to estimate contribution of bearing friction; for the remainder of this work, the behaviour of bearing friction is not considered or discussed further.
5.3.3 Deformation Friction

Figure 5-3 shows deformation friction as a function of contact pressure for both the cylindrical and spherical probes. This figure shows two of the driving parameters of deformation friction namely contact pressure (normal load) and sliding speed, where
increasing these two parameters results in increases in deformation friction. The contact pressure was estimated from static contact measurements using Hertz contact theory and therefore are approximate (discussed in chapter 6). This figure nonetheless provides a clear picture of deformation friction. For the spherical probe, contact pressures in the range of 12-17 kPa were achieved, while, for the cylindrical probe, contact pressures between 17-29 kPa were achieved. The two probe geometries coincide at 17 kPa where deformation friction appears to be higher for the spherical probe compared with the cylindrical probe. Overall, there is a clear trend that shows increasing sliding speed and contact pressure increases deformation.

Figure 5-3: Deformation friction as a function of contact pressure for the cylindrical and spherical probes (based on contact areas for cylindrical and spherical probes discussed in chapter 5).

Figure 5-4 and 5-5 show deformation friction as a function of sliding speed for the cylindrical and spherical probes respectively. Each data point is an average taken from all three probe materials and calculated using equation 5-4. Averaging was carried out because deformation frictions from all three probes were very similar. Further, lubrication had negligible effect on deformation friction. This is indicative of pure rolling where probe material and lubrication have negligible effect on deformation friction (Greenwood et al, 1957). Therefore, figures 5-4 and 5-5 are representative of
deformation friction of different probe materials and lubrication states for a given geometry. This has an important implication when calculating adhesion friction for the dry and lubricated contacts (water and oil), since the same deformation friction values can be assumed to be present in all three contact cases.

Figure 5-4: Deformation friction as a function of sliding speed for the cylindrical probe at three normal loads (each data point is an average of data measured for aluminium, Noryl and PTFE probes).

Figure 5-5: Deformation friction as a function of sliding speed for the spherical probe at three normal loads (each data point is an average of data measured for aluminium, Noryl and PTFE probes).
The results show that for the cylindrical and spherical probes, the deformation friction increases with increasing normal load and sliding speed. Pioneering work by Grosch, (1963) on rubber showed sliding friction increases with sliding speed and this was related to the material’s loss tangent. The loss tangent is defined as the ratio of the storage modulus which is the in-phase component of the dynamic modulus (ratio of stress and strain) and the loss modulus which is the out-of-phase component of the dynamic modulus of the material. Grosch, (1963) showed that maximum friction coincided with the maximum value of the loss tangent. In this study, this property was not investigated but rather another property termed the loss-radius factor is used to explore the change of deformation friction with sliding speed. The loss-radius factor is derived following a re-arrangement of Greenwood et al, (1961) equations 2-12 and 2-13 (chapter 2, section 2-3-3-3). These equations have been reproduced below.

\[ F_c = \frac{\alpha 2 W a}{3 \pi R} \]  
Equation 2-12

\[ F_s = \frac{\alpha 3 W a}{16 R} \]  
Equation 2-13

where c/s – subscripts stands for cylinder and sphere respectively, W – normal load, R-sphere/cylinder radius, a – contact radius, \( \alpha \) – hysteresis loss factor

By rearranging equation 2-12 and 2-13, all the known variables are moved to the left hand side and the unknown variables to the right hand side. This is done since the hysteresis loss and contact radius are dynamic properties of the contact which are not measured in this study and would be particularly difficult to measure dynamically. The resulting rearrangement is termed the loss-radius factor (lrf) which is a function of hysteresis loss and contact radius (the constants \( 2/3 \pi \) and \( 3/16 \) in equation 2-12 and 2-13 have been replaced with C (a probe dependent parameter) in equations 5-6 and 5-7 respectively):

**Equation 5-6: Loss-radius factor for the cylindrical probe**

\[ (lrf)_c = \frac{F_c R_c}{W} = \alpha a_c C_c \]

**Equation 5-7: Loss-radius factor for the spherical probe**

\[ (lrf)_s = \frac{F_s R_s}{W} = \alpha a_s C_s \]
where, $C_c/C_s$ is a constant (cylinder/sphere), $\alpha$ is hysteresis loss factor, $a$ is contact radius (mm).

**Figure 5-6:** Loss-radius factor as a function of sliding speed for the cylindrical probe

**Figure 5-7:** Loss-Radius Factor as a function of sliding speed for the spherical probe
Figure 5-6 and 5-7 show $lrf$ as a function of sliding speed. These figures show that the increase in deformation friction is due to the combined effect of hysteresis loss and contact radius. Figure 5-6 and 5-7 are not entirely independent of normal load. To isolate the effect of sliding speed alone on the loss-radius factor ($lrf$), the effect of normal load is factored out from the right hand side of equations 5-6 and 5-7 to give a parameter which is termed the modified loss radius factor given by equations 5-8 and 5-9. This modification is achieved by plotting loss-radius factor ($lrf$) as a function of normal load and fitting for the normal load dependence. The dependence of $lrf$ on normal load for the spherical probe is minimal (see figure 5-7). The empirically modified loss-radius equations for the cylindrical and spherical probes are:

**Equation 5-8: Modified loss-radius factor**

$$(lrf)_{cm} = \frac{(lrf)_c}{W^{1/5}} = F_c \frac{R_c}{W^{1/5}} = \alpha a_{cm} C_c$$

**Equation 5-9: Modified loss-radius factor**

$$(lrf)_{sm} = \frac{(lrf)_s}{W^{1/10}} = F_s \frac{R_s}{W^{1/10}} = \alpha a_{sm} C_s$$

where $(lrf)_{cm}$ is the modified loss factor for the cylindrical probe (mm/N$^{(1/5)}$), $(lrf)_{sm}$ is the modified loss factor for the spherical probe (mm/N$^{(1/10)}$), $a_{cm}$ is the modified contact radius for the cylinder and $a_{sm}$ is the modified contact radius for the sphere.

The contribution of normal load to the loss-radius factor is $\sim W^{1/5}$ for the cylindrical probe and for the spherical probe it is $\sim W^{1/10}$. These contributions are based on fitted data and have been rounded to 1 decimal point. Figures 5-8 and 5-9 show that the modified loss-radius factors varies as a function of sliding speed for both the cylindrical and spherical probes, supporting the hypothesis that deformation is a function of sliding speed for a given normal load (Persson, 1998). Since the loss-radius factor consists of a constant, hysteresis loss and contact radius, figure 5-8 and 5-9 indicate that the increase of deformation friction with increasing sliding speed is due to the combined effect of increasing hysteresis loss and contact radius. This does not mean both parameters are increasing. In general, as sliding speed increases, viscoelastic materials stiffen, and hence, contact radius would decrease. If this assumption is true, then the increase in deformation friction is due to the increase in hysteresis loss with sliding speed with
negligible effect of contact radius. This assumption has a further implication, hysteresis loss does not increase indefinitely but peaks and then decreases (see figure 2-14). Since within this study, deformation friction is seen to plateau close to 300 mm/s, it is reasonable to assume that we are close to the peak.

Two empirical relationships were developed (equations 5-10 and 5-11) that estimate deformation friction incorporating sliding speed for the cylindrical and spherical probes:

**Equation 5-10: Deformation Friction for the Cylindrical Probe**

\[ F_C = \frac{W}{R_C} \times 0.2 \times v^{0.21} \]

The constant 0.2 has dimensional units of \((N^{(1/5)} \times m^{0.79} \times t^{0.21})\)

**Equation 5-11: Deformation Friction for the Spherical Probe**

\[ F_s = \frac{W}{R_s} \times 0.6 \times v^{0.13} \]

The constant 0.6 has dimensional units of \((N^{-(1/10)} \times m^{0.87} \times t^{0.13})\)

It is important to note the dimensions of the constants arise from the fitting process. The underlying parameters such as the tangent loss and elastic modulus were not measured in this present study but their consideration in future work would provide simpler dimensions for the constants.

![Cylinder: Modified Loss-Radius Factor as a function of Sliding Speed](image)

*Figure 5-8: Modified Loss-Radius Factor for the cylindrical probe (dataset includes low, medium and high normal loads and the line of best fit is taken: v-sliding speed)*
These set of experiments investigating deformation friction have elaborated on past work and have shown that deformation friction is a function of normal load and sliding speed for a given geometry. A method has been developed to estimate deformation friction without directly measuring contact radius or hysteresis loss which are dynamic properties (difficult to measure).

The empirical relationships developed estimate deformation friction within the constraints of this study. Important conclusions can be drawn in relation to shaving. Since, normal load and sliding speed are variables controlled by the user and they influence the intrinsic property of skin (hysteresis loss of skin, real contact area and elastic modulus); user behaviour has significant influence on deformation friction (heavy loading, fast shaving strokes etc). Further, deformation friction is also influenced by geometry and this gives the razor designer an opportunity to affect deformation friction. However, this has to be taken in context, since the proportion of deformation friction relative to adhesion friction will ultimately determine its overall effect on total measured skin friction (discussed in section 5-3-7, 5-3-8 and 5-3-9).
5.3.4 Adhesion Friction Dry Contact

Figures 5-10, 5-11 and 5-12 show adhesion friction as a function of sliding speed for the cylindrical probes (aluminium, PTFE and Noryl respectively) and figure 5-13 (aluminium) shows adhesion friction as a function of sliding speed for the spherical probes based on equation 5.5. The results show that for sliding speeds greater than 50 mm/s, adhesion friction is a constant. The variation below 50 mm/s is primarily attributed to the method used to estimate adhesion friction where the interaction at the lower speeds is not independent of deformation friction.

The adhesion curves for all three probe materials (aluminium, PTFE and Noryl) show similar trends. At low speeds (below 50 mm/s) adhesion friction varies with sliding speed but further increase in sliding speed results in a constant value for adhesion friction. The trend is consistent across geometry (see appendix C.1 for the remaining curves for the spherical probes). This result can be understood by considering the rate at which atomic interactions occur e.g. for rubber de-bonding/bonding of a rubber molecule takes $10^{-5}$ seconds, which is 5 orders of magnitude faster than the rates considered in this study (Moore et al., 1972). For this reason, adhesion friction should be independent of rate for the constraints of this study.

PTFE had the lowest overall adhesion friction, followed by Noryl with aluminium having the highest adhesion friction. Adhesion friction data correlated with water contact angle measurements carried out (see table 3-4) for the three probe materials. If water contact angle is indicative of surface energy, then the results show increasing surface energy increases adhesion friction (Elkhyat et al., 2004).

Adhesion friction for the dry contacts is a function of normal load, probe geometry and probe material. These properties are in line with the general effects attributed to skin friction. The coefficient of adhesion friction (between 0.44 and 0.84) is within the wide range of values quoted in literature (between 0.1 and 3).
Figure 5-10: Adhesion Friction as a function of Sliding Speed: Cylindrical Aluminium Probe: Dry

Cylindrical Probe : Aluminium: Dry

- Normal Load 1.1 N
- Normal Load 2.2 N
- Normal Load 2.8 N

Figure 5-11: Adhesion Friction as a function of Sliding Speed: Cylindrical PTFE Probe: Dry

Cylindrical Probe : PTFE: Dry

- Normal Load 1.1 N
- Normal Load 2.2 N
- Normal Load 2.8 N
Figure 5-12: Adhesion Friction as a function of Sliding Speed: Cylindrical Noryl Probe: Dry

Figure 5-13: Adhesion Friction as a function of Sliding Speed: Spherical Aluminium Probe: Dry
5.3.5 Adhesion Friction of Contact with Water

Figure 5-14, 5-15 and 5-16 show the coefficient of adhesion friction as a function of Strubeck number for the water contact situation. The Strubeck number is defined as the ratio of sliding speed multiplied by viscosity divided by normal load and has dimensions of m$^{-1}$. The data for the cylindrical and spherical probes both show adhesion friction decreases with increasing Strubeck number. Further, there is an effect of probe material, where PTFE has the highest adhesion friction, followed by Noryl and finally aluminium. This trend correlates with the water contact measurement carried out for the three probes and show the reverse trend to that of the dry contact. This can be interpreted to mean that the more hydrophobic the probe is, then the higher the adhesion friction.

Aluminium had the lowest contact angle, followed by Noryl and finally PTFE had the highest value.

![Graph showing coefficient of adhesion friction as a function of Strubeck number for water contact.](image)

Figure 5-14: Coefficient of Adhesion Friction as a function of Strubeck Number (cylindrical probe): Water
Figure 5-15: Coefficient of Adhesion Friction as a function of Stribeck Number (Spherical probe): Water

Figure 5-16: Coefficient of Adhesion Friction as a function of Stribeck Number (Aluminium probe): Water

The effect of geometry is shown in figure 5-16 for the aluminium probe, where the spherical probe has an overall higher coefficient of friction compared with the cylindrical probe. A similar trend is seen for the Noryl and PTFE materials (Appendix C.2). The lubrication regime appears to be in the boundary regime, due to the high coefficient of adhesion friction values. The results shows adhesion friction for contacts lubricated with
water is a function of sliding speed, normal load and probe geometry. The effect of probe material is explained by considering the water contact measurements shown in table 3-4. Since aluminium is hydrophilic, it is seen to have the lowest coefficient of adhesion friction, followed by Noryl the next hydrophilic probe and finally, PTFE has the highest coefficient of adhesion friction which is the only hydrophobic probe. Materials which form a more stable water film on their surface are better lubricated by water than materials that do not, therefore, hydrophilic probes have lower coefficient friction compared with hydrophobic probes in the presence of water (Adams et al., (2007)).

5.3.6 Adhesion Friction of Contact with Shaving Oil

Figure 5-17, 5-18 and 5-19 show the coefficient of adhesion friction as a function of the Strubeck number for the oil contact. The Newtonian shaving oil used in this study has a viscosity three times higher than water. Newtonian in this case refers to a fluid that maintains a constant viscosity with varying shear rate. The data show a general trend, where the three probe materials in both geometries have similar coefficient of adhesion friction values that do not vary significantly with the Strubeck number. The lubrication behaviour is in the boundary regime with the exception of the cylindrical Noryl probe (sliding speed of 100 mm/s) which appears to transition to another lubrication regime, characteristic of hydrodynamic lubrication (very low coefficient of adhesion friction values).

The presence of shaving oil in the contact appears to normalise the effect of probe material. Figure 5-19 shows that the effect of geometry for a given material (similar trend seen for Noryl and PTFE, see Appendix C.3), the coefficients of adhesion friction are similar for both the cylindrical and spherical probe. Comparing this trend to that of the water contact case, for the same material (see figure 5-16), it is clear that although shaving oil is a better lubricant than water, its behaviour is more complicated.
Figure 5-17: Coefficient of Adhesion Friction as a function of Strubeck Number (Cylindrical probes): Oil

Figure 5-18: Coefficient of Adhesion Friction as a function of Strubeck Number (Spherical probes): Oil
5.3.7 Relative Proportion of Adhesion and Deformation Friction (Dry Contact)

The relative proportions are calculated simply as:

\[ \text{Relative proportion of Adhesion Friction} = \frac{\text{Adhesion Friction}}{\text{Total Friction}} \times 100 \]

\[ \text{Relative proportion of Deformation Friction} = \frac{\text{Deformation Friction}}{\text{Total Friction}} \times 100 \]

The plots of percentage contribution to total friction as a function of sliding speed depict the 'bigger' picture giving an insight into the relative importance of adhesion and deformation friction to total friction. Further, they show the effect of key parameters (for a given geometry and material) namely normal load and sliding speed in a single graph.

Figures 5-20, 5-21 and 5-22 show the percentage contribution of adhesion and deformation friction as a function of sliding speed for the cylindrical probes made of aluminium, PTFE and Noryl, respectively. There is a remarkable resemblance between all three figures, where the effect of normal load on the relative proportion of adhesion and deformation is negligible in the range considered in this study. The effect of sliding speed is noticeable below <50 mm/s (90-80% due to adhesion friction) but the effect plateaus
beyond this sliding speed (80% due to adhesion friction). This can be attributed to the inherent assumption that deformation and adhesion are independent and can be separated, which is entirely not the case. The results from all three figures show that the primary parameter affecting the proportions of adhesion and deformation friction is probe material and the effect of normal load and sliding speed are negligible.

The effect of probe material is evident with the PTFE probe where the contribution of adhesion friction to total friction is lower (80-70%) compared with the aluminium and Noryl (90-78%) probes. As discussed in section 5.3.4, adhesion friction correlated with surface energy (contact angle measurements) where PTFE had the lowest surface energy and therefore, the lowest adhesion friction. Since, deformation friction is independent of probe material, adhesion friction is lower for PTFE i.e. deformation friction contributes a relatively larger proportion to total friction for the PTFE probe compared with the aluminium and Noryl probes.

![Figure 5-20: Percentage Contribution to Total Friction as a function of Sliding Speed (Cylindrical Aluminium Probe)](image-url)
Figure 5-21: Percentage Contribution to Total Friction as a function of Sliding Speed (Cylindrical PTFE Probe)

Figure 5-22: Percentage Contribution to Total Friction as a function of Sliding Speed (Cylindrical Noryl Probe)
The trends described above for the cylindrical probes are also seen with the spherical probes of the same material. Figure 5-23 shows the percentage contribution to total friction as a function of sliding speed for the spherical PTFE probe. The relative proportions of adhesion and deformation friction are very similar to the corresponding cylindrical probe (figure 5-21). This same trend is also seen for the remaining spherical probes (see Appendix C.4 for aluminium and Noryl figures).

This leads to a reduction in the number of parameters needed to estimate the relative proportions of adhesion and deformation friction for the dry contact. Normal load, geometry and sliding speed (>50 mm/s) have negligible effect on the relative proportions and probe material is the biggest factor affecting the relative proportions of adhesion and deformation friction of dry contacts.

The relative proportions also provide insight into why skin friction researchers consider deformation friction negligible. Skin friction modelling primarily focuses on adhesion friction, the figures above offer a plausible explanation. The normal loads and sliding speeds investigated by many researchers by and large are below <1N and <<100 mm/s respectively, for this reason, it is clear even from our present work, adhesion friction dominates (~90% for aluminium and Noryl, ~80% for PTFE) and the relative
contribution of deformation friction would play an even smaller role as normal loads and sliding speed reduce further. For shaving, there is a wider dynamic range of user behaviours (low, medium and high loading, slow, medium and fast sliding strokes etc) which means that these relative proportions are highly relevant when considering dry skin.

5.3.8 Relative Proportion of Adhesion and Deformation Friction (Water Contact)

The relative proportions plotted in figure 5-24, 5-25 and 5-26 show the same general trend as the dry contact data (figure 5-21, 5-22 and 5-23) where the effect of normal load has negligible effect on the relative proportions of adhesion and deformation friction. But the effect of sliding speed is far more significant where increasing sliding speed (10-300 mm/s) results in a decrease of 20-30% in adhesion friction. The effect of probe material has the reverse effect to that of the dry contact, the more hydrophilic the probe is, the better lubricated the contact is with water. This is evident with aluminium which is hydrophilic (figure 5-24) is compared with PTFE (figure 5-25) which is hydrophobic, PTFE has higher overall relative adhesion friction (92-74%) compared with aluminium (88- 62%). Noryl has contact angle that is between aluminium and PTFE and the results indicate this (90-70%). These trends hold across geometry for both the cylindrical and spherical Noryl probes (figure 5-26 and figure 5-27 respectively) and for corresponding materials (see Appendix C.5 for the remaining figures for PTFE and aluminium).
Figure 5-24: Percentage Contribution to Total Friction as a function of Sliding Speed (Cylindrical Aluminium Probe Water Contact)

Figure 5-25: Percentage Contribution to Total Friction as a function of Sliding Speed (Cylindrical PTFE Probe Water Contact)
Figure 5-26: Percentage Contribution to Total Friction as a function of Sliding Speed (Cylindrical Noryl Probe Water Contact)

Figure 5-27: Percentage Contribution to Total Friction as a function of Sliding Speed (Spherical Noryl Probe Water Contact)
5.3.9 Relative Proportion of Adhesion and Deformation Friction (Oil Contact)

The presence of oil significantly modifies the trends compared with the dry and water contacts, where the role of probe material was prominent and adhesion friction dominated the relative proportions. Figure 5-28, 5-29 and 5-30 show the relative proportion of adhesion friction relative to deformation decreases with sliding speed from 80-70 % to close to 50% for all three probe materials. The relative proportion also shows dependence on normal load which was not the case for the dry and water contacts, where, normal load had negligible effect. These figures show increasing normal load brings the proportions of adhesion and deformation friction close to 50-50%.

![Graph showing relative proportion of adhesion and deformation friction](image)

**Figure 5-28: Percentage Contribution to Total Friction as a function of Sliding Speed (Cylindrical Aluminium Probe Oil Contact)**
Figure 5-29: Percentage Contribution to Total Friction as a function of Sliding Speed (Cylindrical PTFE Probe Oil Contact)

Figure 5-30: Percentage Contribution to Total Friction as a function of Sliding Speed (Cylindrical Noryl Probe Oil Contact)
High normal loads combined with high sliding speeds leads to the relative contribution of adhesion and deformation friction reaching close to 50-50% for all three probe materials. There is a special case for the cylindrical Noryl probe (figure 5-30) where the proportions switch over, this was explained previously and is attributed to a transition from boundary to hydrodynamic lubrication. This results in deformation friction contributing as much as 90% of the total friction. Figure 4-31 shows data for the aluminium spherical probe, the effect of normal load is minimal and the overall effect of sliding speed is also negligible. Similar trend are seen for the spherical probes made of PTFE and Noryl (see Appendix C.6). The proportions for both the cylindrical and spherical probes are similar across all three probe materials with proportions of adhesion friction in the range of 50-70%.

These results collectively oppose the notion that deformation friction can be neglected and adhesion friction dominates skin friction. In the context of shaving, it is clear, as the efficacy of the lubricant increases (becomes more lubricious), adhesion friction will decrease, therefore, the relative proportion of deformation friction will increase and this is what these results point towards. Therefore, deformation friction in such a scenario would be just as important as adhesion friction and would warrant careful consideration.
5.4 Concluding Remarks

This study set out to understand the two constituent components that govern skin friction. The percentage contribution of adhesion and deformation to total skin friction was investigated in terms of five key parameters namely; normal load, sliding speed, probe geometry, probe material and lubrication.

Deformation friction was shown to be a function of normal load and sliding speed. An empirical relationship was developed to account for this dynamic behaviour termed loss-radius factor. The method developed provides a practical way of estimating the effect of contact radius and hysteresis loss which are dynamic properties that are difficult to measure in friction measurements.

Adhesion friction for the dry contact was seen to be independent of sliding speed > 50 mm/s and a function of normal load and probe material. The highest friction was seen for the hydrophilic aluminium probe and the lowest friction for the hydrophobic PTFE probe. These results support similar finding by Elkhyat et al., (2004). The relative proportion of adhesion and deformation friction for the dry contact is therefore a function of primarily probe material, sliding speed (>50 mm/s) and normal load. The effect of probe geometry is negligible.

Lubricating the surface with water, results in adhesion friction reducing with increasing sliding speed. Adhesion friction is seen to be higher for the hydrophobic probe PTFE compared with the hydrophilic probes aluminium and Noryl. This is the reverse of what was seen with the dry condition. This is attributed to the hydrophilic probes forming a more stable water film on their surfaces compared with hydrophobic surfaces. The relative proportions show dependence on probe material and sliding speed with negligible effect of probe geometry and normal load.

The presence of oil modifies the trends significantly. Adhesion friction is lower compared with the dry and water conditions. The relative proportions of adhesion and deformation are a function of normal load and sliding speed leading to proportions close to 50-50% for the cylindrical probes which is a significant shift compared to the dry and water cases. The effect of normal load and sliding speed are more significant on the cylindrical probe than on the spherical probe but in both cases probe material has negligible effect.
The three contact cases investigated (dry, water and oil contacts) have revealed the conditions under which deformation friction becomes significant. Since deformation friction can be considered to be unaffected by probe material and lubrication, the effect of lubricating the surfaces leads to a reduction in adhesion friction, going from dry to water and finally shaving oil. This leads to the overall reduction of the relative contribution of adhesion friction and the increase of the relative proportion of deformation friction to total friction. This is especially the case for the oil contact, where for high normal loads and sliding speeds, deformation friction can contribute as much as 50% of the total friction. This has significant implications, not least that deformation cannot be ignored.

The next chapter will propose empirical models based on the relative proportions of adhesion and deformation friction covered in this chapter. A model for hair cutting friction is also proposed based on single hair cutting data. Further, two case studies are carried out to investigate the relative contribution of adhesion, deformation and hair cutting friction to total shaving friction.
6 SHAVING FRICTION

6.1 Introduction

Chapters four and five detailed two sets of experiments carried out to understand the parameters affecting skin friction. The in-vivo experiment was concerned with quantifying the effect of normal load and nominal surface area on the coefficient of friction. While, this experiment demonstrated the complexity associated with extracting meaningful relationships from a multi-variable experiment, it highlighted the key parameters affecting skin friction which formed the basis for the in-vitro experiments targeted at separating adhesion and deformation using rolling and sliding probes.

The rolling and sliding experiment was carried out under controlled conditions on a deformable substrate that mimics the mechanical properties of skin, thus, eliminating the variations associated with using a group test subjects. This allowed the dependence of friction on key parameters of interest to be ascertained and the percentage contribution of adhesion and deformation friction to total friction to be determined.

This chapter details two models and case studies investigating shaving friction. The first model in section 6.2 takes the form of empirical relationships for the relative proportion of adhesion and deformation friction in terms of normal load, sliding speed, probe material, probe geometry and lubrication.

The second model in section 6.3 is based on a computer simulation model to estimate hair cutting friction. Two key variables are considered in this model namely hair density and hair cutting profile (i.e. force as a function of time during cutting). This model is based on in-vitro single hair cutting data and it is assumed that all hairs in the shave area exhibit the same behaviour.

In order to estimate the relative proportions of the constituent components of shaving friction (adhesion, deformation and hair cutting), two data sets will be combined i.e. the in-vitro skin friction data and the hair cutting friction data. This analysis is presented in section 6.4 in the form of two case studies.
6.2 Skin Friction Model

6.2.1 Scope of the Model

6.2.1.1 Introduction

The skin friction models developed in this section are only valid for the range of conditions over which experiments were carried out. The parameters considered are those investigated in the in-vitro rolling and sliding experiment and they are normal load (contact pressure), sliding speed, probe material, probe geometry and lubrication. In the sub-sections that follow we first review the range investigated for each parameter.

6.2.1.2 Normal Load/ Contact Pressure

The normal load range investigated was from 0.7 to 2.8 N. For the spherical probe, the lower end of this range was used and for the cylindrical probe the higher end of this range was used. The contact pressure is a more useful parameter in this case and will provide a comparison across geometry.

Figure 6-1: Flowchart showing the process used to determined contact area
To determine the pressure, the contact area is estimated using the process shown in figure 6.1. The first step in estimating the contact area is to determine elastic modulus of the skin mimic. This was achieved using a 1-mm diameter cylindrical probe to measure the applied load (~ 0 - 2 N) as a function of displacement (see chapter 3, section 3.3.3.1). From these data, the stiffness was calculated from the applied load divided by displacement. The stiffness is then used in equation 6.1 (Sneddon, 1965) to estimate the elastic modulus, where a Poisson ratio of 0.49 was used (typical value for skin):

\[ E = \frac{K}{2a} (1 - \nu) \]

**Equation 6-1: Elastic Modulus for cylindrical punch** (K – stiffness of the substrate, a – radius of the cylindrical probe, \( \nu \) – Poisson ratio)

The resulting data for the modulus as a function of depth are shown in figure 6-1. The second step was to measure the indentation depth at normal loads that covered the test range for both the cylindrical and spherical probes. This involved using a cylindrical and spherical probe of the same geometry as the rolling and sliding experiment. The test was carried out on the Instron mechanical testing machine. For the cylindrical probe normal loads between 1.1 and 2.8 N were used, and while for the spherical probe loads between 0.7 and 1.3 N were used (same loads as the *in-vitro* experiment). Data from this experiment were used to create plots of force as a function of indentation for both probe geometries. Then, using these data, the elastic modulus range for each probe was estimated from figure 6-2.

The next step was to use the elastic modulus in the Hertz contact equations to estimate the contact radius for both geometries (which is a function of instantaneous load and modulus, where modulus is assumed to be a function of depth of penetration):

\[ a_c = \frac{2}{\sqrt{\pi}} \left( \frac{R_c}{W} \frac{1 - \nu^2}{E} \right)^{\frac{1}{2}} \]

**Equation 6-2: Contact radius for the cylindrical probe**
\[ a_s = \left( \frac{3}{4} R_s W \frac{1 - \nu^2}{E} \right)^{\frac{1}{3}} \]

Equation 6-3: Contact radius for the spherical probe

where, \( a_c \) and \( a_s \) are contact radius for the cylindrical and spherical probes respectively, \( R_c \) and \( R_s \) are the radii for the cylindrical and spherical probes respectively, \( E \) is the elastic modulus, \( \nu \) is the Poisson ratio and \( W \) is normal load and \( \overline{W} \) is normal load per unit length.

\[ \text{Modulus (kPa)} = 9381.5 \times I + 27.2 \]

Figure 6-2: Elastic Modulus as a Function of Indentation for cylindrical 1 mm probe loaded up to ~ 2 N on the skin mimic. Poisson ration (\( \nu \)) of 0.49 was used, I - indentation.

The final step is to calculate the contact area using the contact radius calculated above for each probe. This process yields the estimated values for contact area/pressure for the spherical and cylindrical probes shown in table 6-1.

<table>
<thead>
<tr>
<th>Contact Area Range (mm(^2))</th>
<th>Normal Load (N)</th>
<th>Pressure (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylindrical Probe ((\text{in-vitro}))</td>
<td>60 – 90</td>
<td>1.1 – 2.8</td>
</tr>
<tr>
<td>Spherical Probe ((\text{in-vitro}))</td>
<td>50 – 80</td>
<td>0.7 – 1.3</td>
</tr>
<tr>
<td>Rectangular probes ((\text{in-vivo})) (section 4.10)</td>
<td>380 – 760</td>
<td>0.3 – 13.4</td>
</tr>
</tbody>
</table>

The contact area calculated here is an estimate that does not take into account dynamic changes that might be expected to occur during sliding. For this reason, the contact...
pressures could possibly be higher in dynamic conditions (stiffening of the material reduces contact area at high shear rates). Table 6-1 shows that the contact pressures for the cylindrical probe and the spherical probe are comparable. Table 6-1 shows also that the contact pressures for the *in-vivo* normal load and nominal surface area experiment overlaps with the range covered by the *in-vitro* rolling and sliding experiment. Therefore, the relationships developed in this chapter cover contact pressures relevant to shaving.

### 6.2.1.3 Sliding Speed

The sliding speed range tested in the rolling and sliding experiment was deliberately chosen to cover typical shaving speeds. Shaving stroke speeds range between 100-300 mm/s. The rolling and sliding experiment covered a range between 10-300 mm/s. The model will cover this wider range.

### 6.2.1.4 Probe Material

The choice of probe material (aluminium, Noryl and PTFE) affected the relative proportion of adhesion and deformation friction, in particular, for the dry and water contact cases (as discussed in chapter 5 sections 5.3.7, 5.3.8 and 5.3.9). The frictional behaviour of Noryl was seen to be in-between that of aluminium and PTFE. For clarity, the dry and water contact empirical models will focus on aluminium and PTFE, since these two probes show distinct behaviour that is attributed to their surface energies. For the oil case, the effect of probe material is negligible; therefore, all three probe materials’ data are included.

<table>
<thead>
<tr>
<th>Probe Material</th>
<th>Surface energy (J/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>0.033-0.035</td>
</tr>
<tr>
<td>PTFE</td>
<td>0.016-0.022</td>
</tr>
</tbody>
</table>

Table 6-2 shows the calculated range of surface energy for PTFE and aluminium. The difference in friction between the probes is attributed to this difference in surface energy (section 5.3.4 and 5.3.5).
6.2.1.5 Probe Geometry

The effect of probe geometry appears to be significant in the oil contact case (see Chapter 5, section 5.3.9). For this reason, the empirical model developed here will not include geometry for the dry and water contact cases and only for the oil contact case.

6.2.1.6 Lubrication

The trends presented in chapter 5 section 5.3.7, 5.3.8 and 5.3.9 showed that dry, water and oil contacts had distinct behaviours and for this reason, three models are proposed to estimate the relative proportions of adhesion and deformation to represent these three cases.

6.2.1.7 Summary

This subsection has introduced the scope for each of the parameters that will be considered and used in the following sections. In the next sections several models will be introduced as well as two case studies on shaving friction.

6.2.2 Dry Contact Model

Figure 6-3 shows percentage contribution to total friction as a function of sliding speed for the dry contact. The primary parameter controlling the percentage contribution to total friction is probe material especially in the range of interest i.e. sliding speed between 100-300 mm/s. The surface energy difference between aluminium and PTFE probes is on average 0.015 J/m². This results in a 10% difference in the relative proportion of adhesion and deformation friction.

The effect of probe geometry and normal load are seen to be negligible for the normal loads and geometries considered, thus, this empirical model is applicable across a relatively wide pressure range and is independent of geometry. The empirical equations developed for aluminium and PTFE are shown in table 6-3. All models are fitted using the automatic excel trendline function which uses the least mean square method.

<table>
<thead>
<tr>
<th>Table 6-3: Empirical equations for the dry model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probe Material</td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>Aluminium</td>
</tr>
<tr>
<td>PTFE</td>
</tr>
</tbody>
</table>
6.2.3 Water Contact Model

Figure 6.4 shows the percentage contribution of adhesion and deformation as a function of sliding speed for the water contact situation. The figure shows that there are two parameters controlling the relative proportions namely sliding speed and probe material. For a given probe material, sliding speed changes the relative proportions as much as 25% for the aluminium probe and 15% for PTFE probe. As for the dry model, the effect of probe geometry and normal load are negligible, leading to the same conclusion that the empirical equations in table 6.4 are valid across a wide pressure range and independent of geometry.

Table 6.4: Empirical equations for the water contact model

<table>
<thead>
<tr>
<th>Probe Material</th>
<th>% Adhesion</th>
<th>% Deformation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>$111v^{-0.094}$</td>
<td>$100 - 111v^{-0.094}$</td>
</tr>
<tr>
<td>PTFE</td>
<td>$105v^{-0.055}$</td>
<td>$100 - 105v^{-0.055}$</td>
</tr>
</tbody>
</table>
Figure 6-4: Percentage contribution to total friction as a function of sliding speed. The effect of probe geometry and normal load are negligible ($v$ - Sliding Speed).

6.2.4 Oil Contact Model

Figure 6-5 shows the oil contact data presented in chapter five, section 5.3.9. In this case, the cylindrical and spherical probe data are all presented in a single graph with the exception of the low normal load data for the cylindrical probe, which have been omitted. The low normal load data appeared to be different and in some cases appeared to be associated with a transition to another lubrication regime. For this reason, they were excluded from the analysis. It is clear from this figure that, the cylindrical and spherical probe data are comparable and probe material has negligible effect on the relative proportions. As was discussed in chapter five, section 5.3.9, the relative proportions of adhesion and deformation for the oil contact case were affected by sliding speed, normal load and geometry, for this reason, the appropriate term incorporating normal load and sliding speed i.e. the Stribeck number has been used instead of the sliding speed which was the case for the dry and water contacts. The effect of geometry is taken into account by developing separate models for the cylindrical and spherical probes.
Figure 6-5: Percentage contribution to total friction as a function of the Stribeck Number. The effect of probe material is negligible

Table 6-5: Empirical equations for the oil contact model (SN = Stribeck Number)

<table>
<thead>
<tr>
<th>Probe Geometry</th>
<th>% Adhesion</th>
<th>% Deformation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylindrical Probe</td>
<td>37113(SN)^2 - 1854(SN) + 74</td>
<td>100 - 37113(SN)^2 - 1854(SN) + 74</td>
</tr>
<tr>
<td>Spherical Probe</td>
<td>898(SN)^2 - 145(SN) + 67</td>
<td>100 - 898(SN)^2 - 145(SN) + 67</td>
</tr>
</tbody>
</table>

Figure 6-6 and 6-7 show the percentage contribution as a function of the Stribeck number, where in both probe geometries, the effect of probe material is negligible and on the whole, Stribeck number is the main parameter controlling the relative proportions. The relationship for both geometries has been summarised in table 6-5.
Figure 6-6: Percentage contribution to total friction as a function of the Stribeck Number for the cylindrical probe. The effect of probe material is negligible (SN = Stribeck Number).

% Adhesion = 37113(SN)^2 - 1854(SN) + 74

Figure 6-7: Percentage contribution to total friction as a function of the Stribeck Number for the spherical probe. The effect of probe material is negligible (SN = Stribeck Number).

% Adhesion = 898(SN)^2 - 145(SN) + 67
6.2.5 Summary of the Skin Friction Models

Three sets of empirical models have been proposed to estimate the relative proportion of adhesion and deformation friction for the three lubrication cases, namely dry, water and oil contacts. Table 6-6 summarises the controlling parameters in each model and the range covered (corresponding to the test conditions). For the dry and water contacts, the effect of probe material and sliding speed are the main controlling parameters where the effect of normal load and geometry are negligible. Therefore, the empirical equations developed only consider these two parameters. As for the oil contact case, normal load, sliding speed and geometry are the controlling parameters where the effect of probe material is negligible.

Table 6-6: Summary of the controlling parameters in each model and their range

<table>
<thead>
<tr>
<th>Controlling Parameters</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dry Model</strong></td>
<td></td>
</tr>
<tr>
<td>• Probe Material:</td>
<td></td>
</tr>
<tr>
<td>Aluminium</td>
<td>0.033-0.035 J/m²</td>
</tr>
<tr>
<td>PTFE</td>
<td>0.016-0.022 J/m²</td>
</tr>
<tr>
<td>• Sliding Speed</td>
<td>10 – 300 mm/s</td>
</tr>
<tr>
<td>• Contact Pressure</td>
<td>13–29 kPa</td>
</tr>
<tr>
<td><strong>Water Model</strong></td>
<td></td>
</tr>
<tr>
<td>• Probe Geometry</td>
<td>Cylindrical and Spherical probes</td>
</tr>
<tr>
<td>• Striebeck number</td>
<td></td>
</tr>
<tr>
<td>Cylindrical Probe</td>
<td>0.0011 -0.034 (1/m)</td>
</tr>
<tr>
<td>Spherical Probe</td>
<td>0.0022 – 0.13 (1/m)</td>
</tr>
<tr>
<td>• Contact Pressure</td>
<td></td>
</tr>
<tr>
<td>Cylindrical Probe</td>
<td>25.1 – 29.2 kPa</td>
</tr>
<tr>
<td>Spherical Probe</td>
<td>12.9 – 17.3 kPa</td>
</tr>
<tr>
<td>• Sliding Speed</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10-300 mm/s</td>
</tr>
</tbody>
</table>
Table 6-7: Summary of the empirical equations for the three contact models

<table>
<thead>
<tr>
<th>Model</th>
<th>% Adhesion Friction Equation</th>
<th>% Deformation Friction Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dry Contact</strong> (Sliding speed (v), Probe material)</td>
<td>Aluminium: 94v^{0.031} PTFE: 94v^{0.055}</td>
<td>100 - % Adhesion Friction</td>
</tr>
<tr>
<td><strong>Water Contact</strong> (Sliding Speed, probe Material)</td>
<td>Aluminium: 111v^{0.094} PTFE: 105v^{0.055}</td>
<td></td>
</tr>
</tbody>
</table>
| **Oil Contact** (geometry, Strubeck- Number) | Cylindrical probe: 37113(SN)^2 - 1854(SN) + 73  
Spherical Probe: 898(SN)^2 - 145(SN) + 67 |                               |

Table 6-7 summarises the three models and the controlling parameters. The models provide approximations for a designer depending on the contact conditions of interest. More importantly, they provide the parameters that affect the relative proportion of adhesion and deformation friction depending on the contact conditions. By concentrating on the mechanisms controlling friction (adhesion and deformation), their relative proportions will direct researcher/designer to focus on the parameters having the most effect on friction. For example, from the three models, the dry contact model shows that adhesion friction is dominant; this is reduced when water is applied in the contact and significantly reduced close to 50% in the present of shaving oil.
6.3 Hair Cutting Model

6.3.1 Introduction

The analysis carried out to establish the contribution of hair cutting friction to total shaving friction has the underlying assumption that shaving friction can be separated into two independent contributions, namely, skin friction (discussed section 5.2) and hair cutting friction (to be discussed in the current section). The modelling approach focuses on taking in-vitro single hair cutting data and populating this across a shaving area and then estimating the average hair cutting friction. In this way hair cutting friction is an average calculated from all the single hairs cut.

6.3.2 Modelling Methodology and Setup

Figure 6-8 shows a flowchart of the methodology used for the computer simulation model. The model starts by taking a typical shave stroke area and populating it with hair. This area is taken to be 10 cm long (typical stroke on the cheek) and 3.6 cm wide (width of a typical cartridge). This area is then populated with hair, where each hair can occupy any position within the area except a position already occupied by another hair i.e. hairs are randomised but not overlapping. The hairs in this case are represented by hair cutting profiles, where each hair is represented by the same hair cutting profile; two example hair cutting profiles are shown in figure 6-9 and 6-10.

The hair cutting profiles are acquired using a bespoke hair cutting rig. This rig is composed of two key components, a holder for the hair and an opposing holder for the blade. Either holder can be driven at the desired speed relative to the other. Typically, the blade is driven at speed to cut the hair protruding from the static hair holder. Sensors connected to the blade setup measure the in-plane force as a function of time.

A visual schematic of the shave area is shown in figure 6-11. The representation shown of the shave area is transformed into a matrix and the hair cutting profiles occupy this matrix representing physical hairs. All hairs are randomised i.e. they can occupy any space within the matrix. Individual blades are represented by the start point chosen within the matrix. Therefore, five blades are represented by five starting points spaced by 1 mm (blade spacing). The friction force is calculated in this matrix by adding at each time increment, the force across all the blades, thus, a force as a function of time plot is created and average hair cutting friction subsequently obtained from this plot.
The hair cutting model is based on the following data and assumptions:

- Typical hair diameter of 100 µm is used
- Blade length and spacing of 3.6 cm and 1 mm chosen respectively
- Shave stroke length 10 cm
- Two hair density cases are considered: 20 and 70 (hairs/ cm²)
  - Low density: 20x(3.6 x 10) = 720 hairs in the shave area
  - High Density: 70x(3.6 x 10) = 2520 hairs in the shave area
- Two hair cutting profiles taken from *in-vitro* experiment are considered
  - Profile A (figure 6-9) and B (figure 6-10)
  - These profiles are based on hair cut at speeds between 19-21 cm/s
  - At present, the effect of cutting speed is unknown and not considered as a variable.
- All hairs in the shave area have the same cutting profile e.g. profile A or B
- The same hair can be cut by all five blades (each blade cuts each hair it encounters and the cutting profile is assumed to be unchanged)

![Flowchart of the computer simulation modelling approach](image)

Figure 6-8: Flowchart of the computer simulation modelling approach

The two types of hair cutting profiles shown in figures 6-9 and 6-10 will be used to investigate hair cutting friction. These profiles were measured by colleagues at Gillette. The key features from these two figures are that their maximum cutting force is very similar but they differ in the duration of the cut.
The model was implemented on Matlab, where four test cases were carried out shown in table 6-8. Two variables are investigated namely cut profile and hair density.
Table 6-8: Test Combinations

<table>
<thead>
<tr>
<th>Hair Density</th>
<th>Cut Profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 hairs/cm²</td>
<td>Profile A</td>
</tr>
<tr>
<td>20 hairs/cm²</td>
<td>Profile B</td>
</tr>
<tr>
<td>70 hairs/cm²</td>
<td>Profile A</td>
</tr>
<tr>
<td>70 hairs/cm²</td>
<td>Profile B</td>
</tr>
</tbody>
</table>

Figure 6-11: Key attributes of the shave area

6.3.3 Results

The four cases in table 6-8 were simulated and the hair cutting friction as a function of time plotted. Figures 6-12 to 6-15 show the results from these simulations. The mean and maximum force in each of the four scenarios are summarised in table 6-9.

Table 6-9: Summary data of the four test cases simulated

<table>
<thead>
<tr>
<th>Results</th>
<th>Profile A (Figure 6.9)</th>
<th>Profile B (Figure 6.10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Density (20 hairs/cm²)</td>
<td>Mean: 1.1 N Max: 2.4 N (Figure 6-12)</td>
<td>Mean: 1.8 N Max: 3.7 N (Figure 6-14)</td>
</tr>
<tr>
<td>High Density (70 hairs/cm²)</td>
<td>Mean: 3.7 N Max: 6.1 N (Figure 6-13)</td>
<td>Mean: 6.3 N Max: 9.3 N (Figure 6-15)</td>
</tr>
</tbody>
</table>
Figure 6-12: Hair cutting force as a function of time (Profile A – Low Density)

Figure 6-13: Hair cutting force as a function of time (Profile A – High Density)
Figure 6-14: Hair cutting force as a function of time (Profile B – Low Density)

Figure 6-15: Hair cutting force as a function of time (Profile B – High Density)
The results show that the two variables investigated influence hair cutting friction significantly. The mean hair cutting friction for profile A increases from 1.1 N to 3.7 N for a density increase from 20 to 70 hairs/cm². A similar effect is seen with profile B, where an increase from 1.8 N to 6.3 is observed. For a given density, profile B has a higher mean hair friction compared with profile A. The key difference between the two profiles is the area under the curve, where profile B has a larger area under the curve, hence, higher hair cutting friction overall.

The results from this simulation show that there is a relatively large range in the measured hair cutting friction (1.1 – 6.3 N). The average friction for a shave is around ~2 N and considering the large values estimated by the model for hair cutting friction, it is clear that some of the assumptions need to be refined, since the contribution from just hair cutting is as high as 6.3 N.

### 6.3.4 Hair Cutting Force Equation

The computer simulation model implemented in Matlab provides a platform to fine tune each individual hair and its property, further, the profile of the dynamic hair cutting friction can be ascertained. In order to estimate the average hair cutting force for a single shave stroke, an equation has been developed based on the same variables and assumptions as the computer simulation model.

Equation 6-4 can be used to predict the average hair cutting friction in similar way to the computer simulation model. The equation contains two key variables, N which is the number of hairs in the shave area and $\bar{f}$ which is the average cutting force for a single hair. These two variables are expressed as the number of hairs (N) determined by $\rho$, W, L which are the hair density, width and length of the shave area respectively. $\bar{f}$ is determined from the area of the hair cutting profile $\left(\int_0^T \bar{f}(t) \, dt\right)$ divided by the duration of the stroke (T).
Equation 6-4: Average Hair Cutting Friction for a Single Blade

\[
\bar{F} = N \bar{f} \\
N = \rho WL \\
\bar{f} = \frac{1}{T} \int_0^T f(t)\,dt \\
\bar{F} = \frac{\rho WL}{T} \int_0^T f(t)\,dt
\]

\[\rho \quad \text{Hair density} \]
\[W \quad \text{Width of shave area} \]
\[L \quad \text{Length of shave area} \]
\[T \quad \text{Total Stroke duration} \]
\[\Delta t \quad \text{Time increment} \]
\[f(t) \quad \text{Cutting force per hair} \]
\[\bar{f} \quad \text{Average cutting force per hair} \]
\[\bar{F} \quad \text{Average friction force across shave area} \]
\[N \quad \text{Number of hair in the shave area} \]

Table 6-10: Comparison between the computer simulation model and equation

<table>
<thead>
<tr>
<th>Method</th>
<th>Hair Density</th>
<th>Profile A</th>
<th>Profile B</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Computer simulation Model</strong></td>
<td>Low Density</td>
<td>Mean: 1.1 N</td>
<td>Mean: 1.8 N</td>
</tr>
<tr>
<td></td>
<td>High Density</td>
<td>Mean: 3.7 N</td>
<td>Mean: 6.3 N</td>
</tr>
<tr>
<td><strong>Equation 6-4</strong></td>
<td>Low Density</td>
<td>Mean 1.1 N</td>
<td>Mean 1.9 N</td>
</tr>
<tr>
<td></td>
<td>High Density</td>
<td>Mean 3.7 N</td>
<td>Mean 6.4 N</td>
</tr>
</tbody>
</table>

The results from the computer simulation model and the equation are in agreement (table 6-10). Therefore, the equation provides a complementary method of estimating the average hair cutting friction.

**6.3.5 Discussion**

The model presented to estimate the contribution of hair cutting friction has shown that the values of hair cutting friction are relatively high compared to typical shaving friction data (1-3 N). This assertion was investigated by comparing *in-vivo* data from a specifically designed shave experiment. The experiment consisted of taking two shaving strokes, a pre stroke (hair present) and a post stroke (no hair present), the difference was taken to be the contribution of hair cutting friction. The results are summarised in table 6-11 for
10 panellists. While this method has many of the issues associated with in-vivo experiments, it provides a relevant comparison nonetheless.

Table 6-11: Hair Cutting Friction from an in-vivo Shaving Experiment (Hair Cutting Research, Gillette)

<table>
<thead>
<tr>
<th>Panellist</th>
<th>Pre Friction-Hair Present (Mean) (N)</th>
<th>Post Friction-No Hair Present (Mean) (N)</th>
<th>Hair Cutting Friction (Mean) (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.70</td>
<td>0.55</td>
<td>0.15</td>
</tr>
<tr>
<td>2</td>
<td>0.67</td>
<td>0.53</td>
<td>0.14</td>
</tr>
<tr>
<td>3</td>
<td>0.90</td>
<td>0.56</td>
<td>0.34</td>
</tr>
<tr>
<td>4</td>
<td>0.60</td>
<td>0.54</td>
<td>0.06</td>
</tr>
<tr>
<td>5</td>
<td>0.61</td>
<td>0.36</td>
<td>0.25</td>
</tr>
<tr>
<td>6</td>
<td>0.46</td>
<td>0.32</td>
<td>0.13</td>
</tr>
<tr>
<td>7</td>
<td>0.97</td>
<td>0.50</td>
<td>0.47</td>
</tr>
<tr>
<td>8</td>
<td>0.46</td>
<td>0.26</td>
<td>0.20</td>
</tr>
<tr>
<td>9</td>
<td>0.77</td>
<td>0.56</td>
<td>0.20</td>
</tr>
<tr>
<td>10</td>
<td>0.91</td>
<td>0.32</td>
<td>0.59</td>
</tr>
</tbody>
</table>

The highest hair cutting friction measured in-vivo is 0.59 N, compared with the computer simulation model which was 6.4 N, it is clear, the model is over predicting. The lowest estimated hair cutting friction from the model is 1.1 N for profile A with low density shave area, which is approximately twice as high as the highest in-vivo measured data.

The primarily reason for this over prediction is due to the assumption that all hairs in the shave area are cut and that all five blades cut every hair they encounter. In order to refine these assumptions, detailed in-vitro and in-vivo experiments are required to estimate the probability associated with cutting a single hair. The probabilities can easily be incorporated into equation 6-4 and the computer simulation model. Further, the profiles considered in this modelling process were based on in-vitro hair cutting data and how representative these are of in-vivo single hair cutting profiles is unknown at present. The framework developed in this body of work provides an excellent starting point where initial assumptions can be refined and the model made more accurate.

6.3.6 Summary of the Hair Cutting Friction Model

The contribution due to hair cutting on total shaving friction was estimated using two approaches. The first approached used a computer simulation method, where each hair was modelled in terms of its cutting profile and the dynamic hair cutting friction estimated. Two variables were investigated namely hair density and hair cutting profile. The two hair cutting profiles considered had the same peak force but differed in the
duration of the profile i.e. area under the curve. Increasing the area under the curve increases hair cutting friction. For a given hair cutting profile, increasing hair density from 20 hairs/cm² to 70 hairs/cm² significantly increased hair cutting friction. The highest hair cutting friction was observed for the hair cutting profile with largest area under the curve combined with a high hair density shave area.

The second approach estimated the hair cutting friction using an equation based on the same assumptions and variables as the computer simulation model. The two approaches were in agreement and showed hair cutting friction is significantly influenced by hair density and hair cutting profile.

The data from the model/equation are significantly higher than in-vivo estimates of hair cutting friction. The discrepancy is attributed primarily to two assumptions made; one is that all the hairs in the shave area are cut and the second is that all five blades cut all hairs they encounter. While, these two assumptions might appear to be the same, they differ in that, the first assumption relates to the efficacy of the blades in cutting hair, while the second relates to the number of blades cutting a given hair.

In order to refine these assumptions detailed in-vivo and in-vitro experiments focusing on single hair cutting are required. These experiments will shed light on the probabilities associated with hair cutting which can be incorporated into the model and equation developed in this body of work.

6.4 Case Studies

6.4.1 Introduction

The approach used to tackle the research problem as a first approximation was based on considering skin friction and hair cutting friction separately. The models developed in the last two sections of this chapter have highlighted the key parameters controlling shaving friction. In this section, two case studies will be considered where the relative proportions will be recalculated taking hair cutting friction into account.

6.4.2 Friction in Shaving

Shaving friction is composed of two main components, namely, skin friction (adhesion and deformation) and hair cutting friction. The assumption that these two components can be considered separately is reasonable, since, it is undesirable for the blades to
interact with the skin, hence, any interaction between the blades and the skin can be considered as skin friction instead of hair cutting friction. This classification has been very important thus far, allowing key parameters affecting each case to be investigated in isolation.

![Diagram showing contributions to shaving friction and case studies](image)

**Figure 6-16**: A schematic diagram showing the contributions to shaving friction and the two case studies investigated

The skin friction models proposed in section 6.2 were based on the relative proportions of adhesion and deformation. In this section, the contribution of hair cutting friction and skin friction to total friction will be calculated. Thus, the relative contribution of the constituent components of shaving friction will be determined.

In the context of the present body of work, wet shaving is the primary focus, for this reason, the dry contact case will not be considered. The two cases that will be considered are the water and oil contact cases. For these two contact scenarios, the relative proportion of adhesion, deformation and hair cutting friction will be determined.

In order to estimate the relative proportion of adhesion, deformation and hair cutting friction, several sets of data will be combined i.e. the water/oil contact data and the hair
cutting friction data from equation 6-4 and in-vivo hair cutting friction data from table 6-11. An important observation regarding this comparison is that, the water/oil contact models of skin were shown to be a function of several parameters, these parameters are assumed to have no affect on the hair cutting friction data i.e. hair cutting friction and skin friction are independent. Figure 6-16 shows a schematic diagram of the contribution to shaving friction and the two case studies. Table 6-12 summarises the cases that will be investigated to gain insight into the percentage contribution of adhesion, deformation and hair cutting friction to shaving friction. For skin friction, there exists three possible variables namely, lubrication, probe material and probe geometry. For hair cutting friction, the two variables considered are hair cutting friction based on profile A – Low density and the in-vivo hair friction data from table 6-11 (panellist 10).

Table 6-12: Combination matrix for the comparison of skin friction with several hair cutting friction cases

<table>
<thead>
<tr>
<th>Shaving Friction = Skin Friction + Hair Cutting Friction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Water</td>
</tr>
<tr>
<td>2. Water</td>
</tr>
<tr>
<td>3. Water</td>
</tr>
<tr>
<td>4. Water</td>
</tr>
<tr>
<td>5. Water</td>
</tr>
<tr>
<td>6. Water</td>
</tr>
<tr>
<td>7. Water</td>
</tr>
<tr>
<td>8. Water</td>
</tr>
</tbody>
</table>

| 1. Oil| Aluminium –Cylindrical Probe + Profile A Low Density |
| 2. Oil| Aluminium –Cylindrical Probe + in-vivo |
| 3. Oil| Aluminium –Spherical Probe + Profile A Low Density |
| 4. Oil| Aluminium –Spherical Probe + in-vivo |
| 5. Oil| PTFE –Cylindrical Probe + Profile A Low Density |
| 6. Oil| PTFE –Cylindrical Probe + in-vivo |
| 7. Oil| PTFE –Spherical Probe + Profile A Low Density |
| 8. Oil| PTFE –Spherical Probe + in-vivo |
6.4.2.1 Water Contact and Hair Friction Model

The inclusion of hair cutting friction significantly modifies the relative proportions of adhesion and deformation friction. The skin friction model discussed in section 6.2 showed negligible effect of probe geometry and normal load. This is not the case when hair cutting friction is included in the proportions. For this reason, eight figures have been produced for each possible combination, four for each probe material (Aluminium and PTFE) e.g. aluminium cylindrical probe – Profile A – Low Density.

Figures 6-17, 6-18, 6-19 and 6-20 show the first set of combinations for the aluminium probe, where the percentage contribution of adhesion, deformation and hair cutting friction to total friction as a function of sliding speed are plotted. Two probe geometries are considered i.e. the cylindrical and spherical probes. Two hair cutting friction data are also considered, data based on profile A – Low density (table 6-10) and the in-vivo data from panellist number 10 (table 6-11). A similar set of figures have also been created for the PTFE probe shown in Appendix D.1.

The trends from all four figures show a complex relationship between the three constituent components of shaving friction. In all the cases, several effects are present.
namely normal load, probe geometry, sliding speed and the hair cutting friction profile used.

For the aluminium cylindrical probe (figure 6-17 and 6-18), deformation friction contributes between 10-25% for both hair cutting friction cases (profile A and \textit{in-vivo}), while adhesion friction is a function of sliding speed and normal load and contributes between 20-70%. The remaining proportion is due to hair cutting friction and varies depending on the hair cutting profile considered, where profile A contributes between 30-70% (figure 6-17) while for the \textit{in-vivo} case between 20-50% (figure 6-18).

For the spherical probe (figure 6-19 and 6-20), deformation friction contributes between 5-20%. The contribution of adhesion friction depends on the hair cutting friction profile considered (similar to the cylindrical probe), for profile A, adhesion friction contributes between 20-45% (figure 5-19), the remaining proportion of 45-70% is due to hair cutting friction. For the \textit{in-vivo} case, adhesion and hair cutting friction are comparable and contributes 30-60% (figure 6-20). Similar trends are seen for the PTFE probe for both geometries (see appendix D.1).

\begin{figure}[h!]
\centering
\includegraphics[width=\textwidth]{aluminium_cylindrical_probe_in_vivo_water_contact_graph.png}
\caption{Aluminium Cylindrical Probe + \textit{In-vivo} (0.59 N)}
\end{figure}

\textbf{Figure 6-18:} Percentage contribution of adhesion, deformation and hair cutting friction as a function of sliding speed for the aluminium cylindrical probe with \textit{in-vivo} hair cutting friction data (water contact)
The results collectively show several important trends. Firstly, the contribution of deformation friction is approximately between 5-25% of the total shaving friction. This...
is not affected significantly by increasing hair cutting friction from 0.59 N for the *in-vivo* case to 1.1 N for the profile A case. Comparing deformation friction with only adhesion friction, its contribution was between 10-30%, its proportion has not significantly changed with the inclusion of hair cutting friction. Secondly, adhesion friction is not the overall dominant force when hair cutting friction is included. For the hair cutting friction cases considered in this case study, it is clear that the *in-vivo* hair cutting friction is comparable to adhesion friction and leads to on average a 40-40% contribution to total friction respectively for both forces. Increasing hair cutting friction (profile A-low density), leads to hair cutting friction dominating the relative proportions, where it can contribute as much as 70% of the total friction (figure 6-17). Therefore, adhesion and hair cutting friction are the primary forces contributing the bulk of the measured shaving friction for the water contact case. The controlling parameters are sliding speed, normal load, probe geometry and hair cutting profile.

**6.4.2.1 Oil Contact and Hair Friction Model**

The previous case considered water as the lubricant; in this case, the lubricant considered is shaving oil. The proportion of adhesion and deformation friction without hair cutting friction was shown to be dependent on sliding speed, normal load and geometry (section 6.2). Similar to the water contact case, the proportions are significantly changed with the inclusion of hair cutting friction. The primary difference between the water and oil contact case was that the percentage contribution of adhesion and deformation contribution were much closer for the oil case, typically converging to 50-50% (adhesion – deformation contribution) at high normal loads and sliding speeds; therefore, the contribution of deformation friction was relatively larger in the oil case compared with the water contact case.

Figure 6-21, 6-22, 6-23 and 6-24 show percentage contribution to total friction as a function of sliding speed for the aluminium material. For the cylindrical probe, deformation friction contributes between 10-30%, at the higher end of this range; it is comparable to both adhesion and hair cutting friction. The relative contribution of adhesion friction is significantly influenced by the hair cutting friction case considered (profile A or *in-vivo*). For the *in-vivo* hair cutting friction case, its contribution is comparable to adhesion friction, each contributing on average 35% (figure 6-22), while
for the hair cutting friction based on profile A, adhesion contributes 20-30% and hair cutting friction 50-70% (figure 6-21).

For the spherical probe, the contribution of hair cutting friction is significantly larger than adhesion and deformation friction (figure 6-23 and 6-24), where on average the contribution is between 50-80%. The effect is more pronounced, as the hair cutting friction increases, deformation and adhesion friction reduce in proportion accordingly. This indicates that hair cutting friction dominates the contribution to total shaving friction for the spherical probe. Similar trends are also seen for the PTFE probe in both geometries (see Appendix D.2).

![Figure 6-21: Percentage contribution of adhesion, deformation and hair cutting friction as a function of sliding speed for the aluminium cylindrical probe with profile A - Low density hair cutting friction data (oil contact)]
Figure 6-22: Percentage contribution of adhesion, deformation and hair cutting friction as a function of sliding speed for the aluminium cylindrical probe with in-vivo hair cutting friction data (oil contact).

Figure 6-23: Percentage contribution of adhesion, deformation and hair cutting friction as a function of sliding speed for the aluminium spherical probe with profile A - Low density hair cutting friction data (water contact).
The results from all four figures show that adhesion and deformation friction on average contribute comparable proportions ranging between 10-30%, while the rest is due to hair cutting friction which can be as high as 80% of the total friction. Based on the current dataset with the limitations already discussed for both the skin friction and hair cutting data, it is clear that the proportion of hair cutting friction increases with increasing lubricant efficacy. This is significantly different to the water contact case, where adhesion and hair cutting friction were comparable on the whole and deformation friction was significantly lower. This leads to an important conclusion that lubrication plays a significant role in the proportions of adhesion, deformation and hair cutting friction.

**6.4.3 Summary of the Case studies**

Two case studies were carried out to understand the influence of hair cutting friction on the relative proportions of adhesion and deformation friction. The results for the water contact case showed that adhesion and hair cutting friction contributions were comparable on the whole (40-40%) and the contribution of deformation friction was lower (10-30%). The hair cutting profile considered also plays an important role in influencing the proportions, where profile A results in hair cutting friction contributing as much as 70% of the total friction. For the oil contact case, the contribution was
dominated by the hair cutting friction, contributing as much as 80% of the total friction. These results lead to the conclusion that lubrication is an important parameter that significantly modifies the relative proportions of adhesion, deformation and hair cutting friction.

### 6.5 Concluding Remarks

This chapter proposed two models. The first focused on modelling the relative contribution of adhesion and deformation friction in terms of lubrication, normal load, sliding speed, probe material and probe geometry. The second model proposed a method for estimating hair cutting friction using computer simulation. The data from these two sets of models were combined (assuming skin friction and hair cutting friction are independent but add to form shaving friction). The purpose of combining these data was to establish the relative contribution of adhesion, deformation and hair friction on shaving friction and the parameters affecting these relationships.

For the dry and water contact models of skin friction, the relative contribution of adhesion and deformation is primarily controlled by probe material and sliding speed, where, the effect of normal load and probe geometry are negligible. For the oil contact model, the controlling parameters are normal load, sliding speed and probe geometry, where, probe material has negligible effect on the relative proportions of adhesion and deformation friction.

The hair cutting friction model developed was based on single hair cutting data and a virtual shave area simulated using two hair cutting profiles for two different hair densities. The results showed that hair cutting friction is governed by the area under the curve (duration of the cut). Increasing this area, increases hair cutting friction. Further, the higher the hair density, the larger the friction. Further work is required to refine the model to take into the probabilities associated with multiple-hair cutting by several blades and the properties of hairs in a given shave area.

The two case studies investigated served to show hypothetically how hair cutting friction affects the relative contribution of adhesion and deformation friction to shaving friction. The results showed that the contribution of hair cutting friction depends on the type of hair cutting profile considered and more significantly, the lubrication of the contact.
Further experimental work is required to establish the contribution of adhesion, deformation (skin friction) and hair cutting friction to shaving friction.
7 CONCLUDING REMARKS

7.1 Introduction

This body of work set out to achieve the following aims:

- To identify key parameters affecting skin friction
- To identify key parameters affecting hair cutting
- Develop test methodologies to quantify their effect
- Develop a model of shaving friction based on skin friction and hair cutting friction.

The approach taken involved breaking down the problem into two separate components that were at first approximation considered independent, these two components were skin friction and hair cutting friction.

Skin friction was investigated using two sets of detailed experiments. The first was an in-vivo experiment involving 20 subjects focusing on understanding the effect of normal load, nominal surface area and anatomical site on skin friction while accounting for the effect of sliding speed, temperature and humidity. The second was an in-vitro experiment designed to overcome the challenges associated with in-vivo testing, by utilising a substrate that replicates the surface and bulk properties of skin. The experiment was designed to establish the relative contribution of adhesion and deformation friction to total skin friction. Applying the insights gained from the in-vivo experiment, the experiment investigated the effect of normal load, sliding speed, probe geometry, probe material and lubrication on the relative proportion of adhesion and deformation.

Hair cutting friction was investigated using two different approaches. The first approach utilised a computer simulation model, where a virtual shave area based on single hair cutting profiles was created. These hair cutting profiles were acquired from in-vitro hair cutting tests. The computer simulation model investigated the effect of hair density and hair cutting profiles on hair cutting friction. The second approach involved using an equation developed with the same assumptions as the computer simulation model to estimate the average hair cutting friction.

Three models were proposed for skin friction based on the relative proportions of adhesion and deformation friction. These models covered the three contact cases.
considered namely dry, water and oil contacts. Two case studies based on the water and oil contacts were conducted to investigate the effect of hair cutting friction on the relative proportions of adhesion and deformation friction. These cases studies served to elucidate the relative significance of each component namely adhesion, deformation and hair cutting friction on a shaving stroke.

7.2 Key Findings

7.2.1 Skin Friction (in-vivo):

Researchers in the field of biotribology have shown in many publications that skin friction does not follow Amontons’ laws and that coefficient of friction of skin is inversely proportional to normal load. This result has been shown for normal load <1 N and very slow sliding speeds. The normal load and nominal surface area experiment carried out on 20 subjects confirmed these results. Further, it was shown to hold for normal loads and sliding speed of up to 12.9 N and 220 mm/s respectively.

Further, the experiment showed that anatomical site, nominal surface area and lubrication influenced skin friction. The exact relationship between each parameter and skin friction could not be ascertained from the in-vivo experiment. This was due to the multitude of variables associated with skin friction which were not controlled directly including sliding speed, humidity, temperature and more crucially the subject to subject variations. Applying lubricant on the surface of skin reduced this variation but not enough to deduce meaningful relationships between the parameters of interest and skin friction. Inherently, the biggest limitation is lack of control, the ability to incrementally vary each parameter of interest while maintaining the rest constant. This is extremely difficult on skin in general and even more difficult on an area such as the face. These results collectively point towards an overwhelming conclusion that in-vivo testing on the face in its present form, is incapable of quantifying the effects of key parameters on skin friction.

7.2.2 Skin Friction (in-vitro)

A practical alternative to in-vivo testing is in-vitro testing based on the skin mimic, which mimics the surface and bulk properties of skin. The in-house development of such a substrate lead to a real alternative that shifted focus from in-vivo to in-vitro testing, which overcame many of the challenges of in-vivo skin testing. The skin mimic eliminates
variations associated with subjects by replicating a mean subject. The skin mimic has been shown to be comparable to skin in terms of its surface and bulk properties as well as being repeatable and reproducible in terms of friction.

The use of the skin mimic allowed two mechanisms attributed to friction, namely, adhesion and deformation friction to be separated and their relationships determined for normal loads and sliding speeds relevant to shaving. An important question in biotribology is the relative proportion of each mechanism on total friction. It has been often theoretically estimated and experimentally found that deformation friction contributes as much as 5% of the total friction on dry skin. These conclusions are based on very limited normal load and sliding speed range, which are not applicable to shaving. Further, shaving is carried out in a wet environment, for this reason, the rolling and sliding experiment was designed to establish the parameters controlling each mechanism and also the percentage contribution of each to total friction. The five parameters investigated were normal load, sliding speed, probe geometry, probe material and lubrication.

The results showed deformation friction is a function of sliding speed, normal load and probe geometry, where the effect of probe material and lubrication were shown to be negligible. This seems to indicate that the surface properties of the interacting materials (probe material) have negligible effect on deformation friction and that deformation friction is controlled by the bulk property of the substrate. It is important to recall that deformation friction in this case refers to hysteresis friction, where the effect of ploughing friction is negligible. Probe roughness was not investigated in this experiment and its role in influencing deformation friction is unknown (discussed further in future work section).

Adhesion friction on the whole is a function of normal load and the effect of probe material depends on the lubricant present on the surface where the dry and water contact cases show probe material dependence, while, for the oil contact there is negligible effect of material probe.

Examining the relative proportion of adhesion and deformation friction reveals the impact of each mechanism on total skin friction. This is an important measure, since it reveals the relative significance of each mechanism. Further, by understanding the effect
of various parameters on the relative proportion of adhesion and deformation friction, skin friction can be manipulated to a desired end.

For the dry contact case, many researchers have shown that adhesion friction to be the dominant mechanism contributing as much as 95% of the total friction. These test were conducted with low normal loads <1 N and sliding speeds of <50 mm/s. The results from the rolling and sliding experiment revealed that this overall trend holds true where on average adhesion friction contributes between 70-90% of the total friction and the remaining proportion of 10-30% is due to deformation friction. The variation is attributed to probe material, where PTFE had the lowest adhesion friction, followed by Noryl and finally aluminium had the highest adhesion friction. Adhesion friction results correlated with contact angle measurements which are indicative of surface energy, where, the higher the surface energy, the higher the adhesion friction. Work by Elkhyat et al., (2004) showed pairing hydrophobic surfaces achieves the lowest friction compared with any other combination e.g. hydrophobic-hydrophilic pairing, while work by Adams et al., (2007) showed no effect of probe material. The present work correlates with Elkhyat et al., (2004) results, where the skin mimic is a hydrophobic substrate and PTFE is a hydrophobic surface, which results in the lowest adhesion friction compared with Noryl and aluminium which are hydrophilic surfaces. The conclusion drawn by many researchers is therefore valid, which is adhesion friction is the dominant mechanism controlling dry skin friction. The relative proportion of adhesion and deformation friction in the dry contact case for sliding speeds >50 mm/s is controlled by probe material, where the effect of normal load, probe geometry and sliding speed are negligible.

For the water contact case, the assertion that probe material controls adhesion friction is evident, where the effect of probe material is reversed compared with the dry contact case. It is hypothesised that the hydrophilic probes (aluminium and Noryl) form a more stable water films on their surfaces compared with the hydrophobic surface (PTFE), for this reason, the hydrophilic surfaces have lower adhesion friction (Adams et al., 2007). This is seen to be the case, where aluminium had the lowest adhesion friction, followed by Noryl and finally PTFE. The relative proportions of adhesion and deformation friction is a function of sliding speed and probe material where, the effects of probe geometry and normal load are negligible. Adhesion friction is still the dominant mechanism where it contributes between 65-90% of the total friction. The remaining 10-35% is due to
deformation friction. The relative proportions of adhesion and deformation friction for both the dry and water contact cases are dominated by adhesion friction, contributing between 65-90% of the total friction.

The oil contact case differs from the dry and water contact cases, where probe material has negligible effect on adhesion friction. Normal load, sliding speed and probe geometry are the controlling parameters. Adhesion friction is a function of the Stribeck number which incorporates normal load and sliding speed. The relative proportion of adhesion and deformation for the oil contact case is a function of normal load, sliding speed (Stribeck number) and probe geometry. For the cylindrical and spherical probes adhesion friction reduces as a function of the Stribeck number. The relative proportion of adhesion friction decreases from 80% to 50% with increasing Stribeck number for the cylindrical probe, while for the spherical probe, adhesion friction decreases from 80 to 55%. The remaining proportion in each case is due to deformation friction. This is a significant shift in the relative proportions compared with the dry and water contact cases and indicates deformation friction contributes a greater proportion (as much as 50%) of the total friction in the oil contact case. This leads to the conclusion that deformation friction cannot be ignored and its contribution is significant in contact cases where adhesion friction becomes comparable to deformation friction. Further, options become available to change skin friction that are not available for the dry contact or have negligible effect in the dry contact case. For example, since deformation friction contributes a significant proportion, parameters affecting deformation friction e.g. the mechanical properties of skin would have a greater influence on skin friction. This opens another avenue to influence skin friction that relies on both the properties of the razor as well as the skin, to take advantage of both adhesion and deformation mechanisms.

7.2.3 Hair Cutting Friction

Hair cutting friction was calculated based on *in-vitro* single hair cutting profiles. Two approaches were undertaken to investigate the effects of two parameters namely the effect of hair density and the effect of different hair cutting profiles. The first approach used a computer simulation model to estimate dynamic hair cutting friction i.e. hair cutting friction as a function of time. The second approach used an equation based on the same assumptions as the computer simulation model to estimate the average hair cutting friction. Both approaches showed increasing hair density in a given shave area, increases
hair cutting friction. As for the effect of hair cutting profile, for profile A which had a smaller area under the curve (force as a function of time) compared with profile B showed increasing the area under the curve resulted in higher hair cutting friction. Comparing hair cutting friction data from the model to in-vivo data, the estimates from the model are significantly higher. The discrepancies between the model and the in-vivo data is attributed primarily to two assumptions made in the model. The first assumption was that every single hair in the shave area is cut and the second is that a single hair can be cut by all five blades. These two assumptions lead to an over estimation of hair cutting friction. The present model and equation developed nonetheless are structured in a way to allow these two assumptions to be refined to incorporate the probabilities associated with hair cutting.

7.2.4 Shaving Friction

The approach used in this body of work was to investigate skin friction and hair cutting friction as two separate problems. The results from both cases were combined to understand the relative proportions of the three constituent components of shaving friction namely adhesion, deformation and hair cutting friction. Within the framework of the present work, the relative proportion of these three components depend on the contact conditions considered as well as the hair cutting profile used to estimate hair cutting friction. Two case studies were undertaken based on the water and oil contacts. The results showed that for the water contact case, adhesion and hair cutting friction contribute on average similar proportions i.e. 40-40% (adhesion – hair cutting friction contribution to total shaving friction), while the remaining proportion is due to deformation friction (20%). These proportions are significantly influenced by the hair cutting profile considered, where, considering profile A can lead to hair cutting friction contributing as much as 70% of the total shaving friction. As for the oil contact case, the contribution of hair cutting friction is more significant and on average contributes as much as 80% depending on the hair cutting profile considered. The remaining proportion is split between adhesion and deformation friction. This leads to a profound conclusion that lubrication can significantly modify the relative proportions of adhesion, deformation and hair cutting friction. By understanding the parameters governing each of the three components, shaving friction can be tailored to a specific end.
7.3 Recommendations and Future Work

The present body of work has placed significant effort and emphasis on establishing parameters that are significant in shaving friction using a combination of *in-vivo* and *in-vitro* methods. However, there are some parameters that have been kept constant in order to simplify the complex tribology of shaving friction and investigating these parameters would lead to new insights.

The literature review highlighted the effect of probe roughness and hydration to be important parameters affecting skin friction. The present work did not investigate these two parameters in a controlled and systematic way and were on average kept constant. These two parameters affect the contact mechanics associated with the probe and skin interaction, where hydration would modify the bulk and shear modulus of skin and probe roughness would modify the contact area. Further, these two parameter affect both adhesion and deformation mechanisms, which would lead to a modification of the relative contribution of each mechanism to total friction. This could be achieved *in-vitro* with skin mimics that have different viscoelastic behaviour to cater for the effect of hydration and probes of various roughnesses. Future work should endeavour to quantify the effect of these two parameters on adhesion and deformation friction.

Hair cutting friction in the present work was highly idealised but nonetheless presented a framework for future work to build on. Firstly, accuracy of the computer simulation model and equation presented could significantly be improved by refining two key initial assumptions. Future work should focus in establishing the probability associated with single hair cutting and probability of repeated cutting by different blades. Secondly, the present work focused on two *in-vitro* hair cutting profiles, it is important to establish the distribution of possible hair cutting profiles based on *in-vivo* single hair cutting data. Further, the effect of sliding speed, blade material, hair hydration on the hair cutting profile have not be considered, investigating the effect of these parameters would lead to a more realistic model of hair cutting friction.

Finally, while the focus of this thesis was on technical measures in particular friction, their effect on subjective measures were not considered. The effect of the relative proportion of adhesion, deformation and hair cutting friction on subjective measures such as glide, comfort, missed hairs etc will create the link between technical and
subjective measurements leading to predicable shaving experience. This would be the next phase of research into shaving friction.
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Appendix A.1: Derivation of Normal load and Friction Force

Figure A1.1 – Diagram showing the derivation of normal load and friction in the anti-clockwise handle direction ($F_d$ - Friction force and $F_N$ - Normal load)

Figure A1.2 – Diagram showing the derivation of normal load and friction force in the clockwise handle direction ($F_d$ - Friction force and $F_N$ - Normal load)
Appendix A.2: Normal load and Nominal Surface Area Testing Protocol

Instructions to panellists (wet)

1. Shave with the razor provided.
2. Wash Face with soap provided and water.
3. Rinse and pat dry.
4. DO NOT APPLY ANY AFTER SHAVE LOTION/BALM
5. Come to S20 at the time arranged (at least an hour after shaving)
6. Prep the face and the operator will take strokes as per the experiment plan.
7. Rinse and re-prep the face
8. The process will be repeated (for different set of conditions, probe and/or load)

Instructions to panellists (dry)

1. Shave with the razor provided.
2. Wash Face with soap provided and water.
3. Rinse and pat dry.
4. DO NOT APPLY ANY AFTER SHAVE LOTION/BALM
5. Go back to your work area (an equilibration period is required before the test)
6. Come to S20 at the time arranged (at least an hour after shaving)
7. The operator will take strokes as per the masterplan
8. The process will be repeated (for different set of conditions, probe and/or load)
### Appendix A.3: Randomised test combination

**Table A3.1: Randomised test conditions for panellist 1**

<table>
<thead>
<tr>
<th>Panellist Number</th>
<th>Load</th>
<th>Probes</th>
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<th>Skin State</th>
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<td>Bony area</td>
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</tbody>
</table>
Appendix B.1: Test Combination for the Rolling and Sliding Experiment

Table B1.1: Test combination for different probe materials and lubrications

<table>
<thead>
<tr>
<th>Probe Material: Aluminium, Noryl and PTFE</th>
<th>Lubrication: Dry, Water and Oil</th>
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<tbody>
<tr>
<td>Probe</td>
<td>Load range</td>
</tr>
<tr>
<td>Cylinder/Sphere</td>
<td>Low Load</td>
</tr>
<tr>
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<tr>
<td>Cylinder/Sphere</td>
<td>Load Level</td>
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</tr>
<tr>
<td>Cylinder/Sphere</td>
<td>Medium Load</td>
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<td>Cylinder/Sphere</td>
<td>High Load</td>
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</tbody>
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Appendix C.1: Dry Contact - Spherical Probes

Figure C1.1: Adhesion friction as a function of sliding speed for the Spherical PTFE probe

Figure C1.2: Adhesion friction as a function of sliding speed for the Spherical PTFE probe
Appendix C.2: Water Contact – Coefficient of Adhesion Friction

Figure C2.1: Coefficient of Adhesion Friction as a function of the Strubeck number for the PTFE (v – velocity, η – viscosity and F\textsubscript{N} – Normal load)

Figure C2.2: Coefficient of Adhesion Friction as a function of the Strubeck number for the Noryl (v – velocity, η – viscosity and F\textsubscript{N} – Normal load)
Appendix C.3: Oil Contact – Coefficient of Adhesion Friction

Figure C3.1: Coefficient of Adhesion Friction as a function of the Stribeck number for the Noryl probe
\((v \cdot \eta \cdot F_N^{-1})\)

Figure C3.2: Coefficient of Adhesion Friction as a function of the Stribeck number for the PTFE probe
\((v \cdot \eta \cdot F_N^{-1})\)
Appendix C.4: Dry Contact - Percentage Contribution of Adhesion and Deformation Friction to Total Friction

Figure C4.1: Percentage Contribution to total friction as a function of Sliding Speed for the aluminium probe

Figure C4.2: Percentage Contribution to total friction as a function of Sliding Speed for the Noryl probe
Appendix C.5: Water Contact - Percentage Contribution of Adhesion and Deformation Friction to Total Friction

Figure C5.1: Percentage Contribution to total friction as a function of Sliding Speed for the aluminium probe

Figure C5.2: Percentage Contribution to total friction as a function of Sliding Speed for the PTFE probe
Appendix C.6: Oil Contact - Percentage Contribution of Adhesion and Deformation Friction to Total Friction

**Spherical PTFE Probe: Oil Contact**

- Deformation Normal Load 0.7 N
- Deformation Normal Load 1.1 N
- Deformation Normal Load 1.3 N
- Adhesion Normal Load 0.7 N
- Adhesion Normal Load 1.1 N
- Adhesion Normal Load 1.3 N

**Spherical Noryl Probe: Oil Contact**

- Deformation Normal Load 0.7 N
- Deformation Normal Load 1.1 N
- Deformation Normal Load 1.3 N
- Adhesion Normal Load 0.7 N
- Adhesion Normal Load 1.1 N
- Adhesion Normal Load 1.3 N

Figure C6.1: Percentage Contribution to total friction as a function of Sliding Speed for the PTFE probe

Figure C6.2: Percentage Contribution to total friction as a function of Sliding Speed for the Noryl probe
Appendix D.1: Water Contact - Percentage Contribution of Adhesion, Deformation and Hair Cutting Friction to Total Friction

Figure D1.1: Percentage contribution of adhesion, deformation and hair cutting friction as a function of sliding speed for the PTFE cylindrical probe with profile A - Low Density hair cutting friction data.
Figure D1.2: Percentage contribution of adhesion, deformation and hair cutting friction as a function of sliding speed for the PTFE cylindrical probe with in-vivo hair cutting friction data.

Figure D1.3: Percentage contribution of adhesion, deformation and hair cutting friction as a function of sliding speed for the PTFE spherical probe with profile A - Low Density hair cutting friction data.
Figure D1.4: Percentage contribution of adhesion, deformation and hair cutting friction as a function of sliding speed for the PTFE spherical probe with \textit{in-vivo} hair cutting friction data.
Appendix D.2: Oil Contact - Percentage Contribution of Adhesion, Deformation and Hair Cutting Friction to Total Friction

**Figure D2.1:** Percentage contribution of adhesion, deformation and hair cutting friction as a function of sliding speed for the PTFE cylindrical probe with profile A - Low Density hair cutting friction data

**Figure D2.2:** Percentage contribution of adhesion, deformation and hair cutting friction as a function of sliding speed for the PTFE cylindrical probe with *in-vivo* hair cutting friction data
Figure D2.3: Percentage contribution of adhesion, deformation and hair cutting friction as a function of sliding speed for the PTFE spherical probe with profile A – Low Density hair cutting friction data.

Figure D2.4: Percentage contribution of adhesion, deformation and hair cutting friction as a function of sliding speed for the PTFE spherical probe with in-vivo hair cutting friction data.
Effect of Normal Load and Nominal Surface Area on Coefficient of Friction of Skin In-Vivo

Duale Mahdi1,2, Alison Riches2, Julie Yeomans2 and Paul Smith2

1 P&G and Gamble, Gillette Innovation Centre
2 University of Surrey, Guildford, Surrey

INTRODUCTION
Skin friction is an important parameter in understanding the interactions between a razor and the skin. Previous studies examining the friction of skin have shown that the frictional force is not proportional to the normal load. Theoretical analysis by Wolfram[1] suggested that the coefficient of friction (μ) is inversely proportional to normal load, N (μ = N⁻¹). Stimson et al. (2) and Kildie et al. (3) showed experimentally that this relationship holds for normal loads up to 1 N. The aim of this investigation is to study normal loads in the range 0.5-13.3 N to understand the relationship between normal load (N) and the coefficient of friction of shaved facial skin at normal loads that are higher than those used previously.

EXPERIMENTAL DETAILS
10 male panelists were probed by a trained operator using an instrumented razor handle (IRH) to which one of three stainless steel probes in place of a razor cartridge were attached (see Figure 1).

The IRH is a device that measures normal and drag loads dynamically. The design allows users to apply normal loads up to 15 N.

The probes were all rectangular in cross-section, varying in cross-sectional area, having a constant length of 3.8 cm and widths of 1.15 and 2.12 cm. The panelist was stroked down the cheek in three overlapping strokes, following a set of specified conditions. The applied load was low, medium, or high.

The anatomical site was either bony or fleshy (see Figure 5) and the skin was dry or lubricated with shave gel. Dry and lubricated tests were conducted on separate days and both cases panelists acclimated for 1 hour prior to the test. Relative humidity (33-52%), temperature (22-26°C) and speed of stroke (2.22 cm s⁻¹) were measured but not controlled. The three normal load ranges, two anatomical sites, three probe sizes and two degrees of lubrication would in 36 separate conditions, which were randomised for each panelist. As each condition was repeated three times (3x3=9) data from a total of 1080 strokes were recorded.

RESULTS
Figure 6 and 7 show the relationship between the coefficient of friction and normal load for dry and lubricated conditions respectively.

The coefficient of friction for both dry and lubricated cases (Figure 6 and 7) demonstrates an inverse relationship with normal load as expected. This relationship is influenced by other factors in the experiment which were not controlled (although they were measured). The box plots (Figure 8 and 9) illustrate the overall effect of probe size.

CONCLUDING REMARKS
This study has investigated the relationship between normal load and coefficient of friction for higher normal loads than used previously. It is clear that lubricated and dry conditions cannot be treated together. In general terms, an inverse relationship between coefficient of friction and normal load was found with dry conditions giving higher coefficients of friction than lubricated. Preliminary analysis suggests that other parameters and their combinations influence the exact form of the relationship.

REFERENCES

Figure E: Poster presented at the biotribology conference in London, 2011
APPENDIX F: Rolling and Sliding Experiment Publication

Rolling and Sliding: Separation of adhesion and deformation friction and their relative contribution to total friction

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2. Department of Mechanical Engineering Sciences, Faculty of Engineering and Physical Sciences, University of Surrey, Guildford, Surrey, Guildford, GU2 7XH

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ABSTRACT
This study is concerned with determining the relative contribution of adhesion and deformation friction using rolling and sliding. The challenges associated with in-vivo friction testing were overcome by utilising a novel substrate that mimics the viscoelastic behaviour and surface texture of human skin combined with a repeatable and reproducible test setup. The results show that in the dry state, deformation friction contributes 20% of the total friction while the remaining proportion is due to adhesion. These proportions are affected by probe material where for PTFE, deformation friction contributes 30% of the total friction. For the lubricated state, the contribution of deformation friction to total friction increases approaching 50-50% at the higher sliding speeds and normal loads investigated.

KEYWORDS
Friction sliding; friction rolling; deformation; adhesion

NOTATION
\(\alpha\) Hysteresis loss
\((brf)_c\) Loss-radius factor (cylinder)
\((brf)_s\) Loss-radius factor (sphere)
\((lrf)_{cm}\) Modified Loss-radius factor (cylinder)
\((lrf)_{sm}\) Modified Loss-radius factor (sphere)
\(F_T\) Total friction
\(F_A\) Adhesion friction
\(F_D\) Deformation friction
\(F_R\) Rolling Friction
\(F_S\) Sliding Friction
\(F_B\) Bearing Friction
\(W\) Normal Load
\(a_c\) Cylinder Contact Radius
\(a_s\) Sphere Contact Radius
\(R_c\) Cylinder radius
1. INTRODUCTION
Friction is an important system property of interacting materials and forms a core part of the study of tribology. An emerging area of tribology termed biotribology deals with the interaction of traditional materials with the human skin both for medical and cosmetic purposes and the present study concerns the latter.

Friction testing on skin presents many challenges especially on areas such as the face. Skin friction has been studied by many researchers e.g. [1-7] on various parts of the human body. The forearm is a common test area chosen because of its accessibility with a tribometer. Parameters including normal load, speed, humidity and temperature, probe material, geometry and test methodology, anatomical site and individual to individual variation have been investigated and shown to affect skin friction [6]. Further, skin is a complicated biological substrate with an elastic modulus ranging between 4.4 kPa and 57 MPa [7]. Controlling test variables in-vivo is particularly difficult, hence in-vitro testing is an attractive alternative which allows variations in the parameters of interest to be made in a controlled manner.

This study utilised a multilayer substrate that mimics the viscoelastic behaviour and surface texture of human skin. The skin mimic was used to investigate the relative contribution of adhesion and deformation friction to total friction in terms of five key variables: normal load, sliding speed, probe material, probe geometry and lubrication.
The two term non-interacting model of friction was used. In this model friction has two components: adhesion and deformation. Adhesion friction arises from the shearing of the bonds between the two interacting surfaces in relative motion. Deformation friction is associated with the incomplete recovery of the substrate due to the viscous loss in one or both of the contacting surfaces (figure 1-1).

In order to separate these two contributions, a Dynamic Friction Instrument (DFI) was used with probes in two modes of operation i.e. rolling or sliding.

![Schematic diagram of probe – substrate interaction (adapted from [2])](image)

The structure of this paper is as follows. In the next section, the non-interacting two term model of friction is discussed and the method used to separate adhesion and deformation friction. Section three covers the experimental details. Section four presents the results and discussion. Section five presents the conclusions drawn from the study and their implications.

2. BACKGROUND THEORY

2.1. Theoretical Considerations

Deformation friction is attributed to two mechanisms: ploughing and hysteresis. Ploughing friction is prevalent in hard-hard contacts e.g. metal-on-metal sliding. For viscoelastic materials e.g. rubber, where hysteresis losses are present, ploughing friction is negligible compared with hysteresis friction [8], [9]. In this study a viscoelastic substrate is used and ploughing friction is not measured. Hysteresis friction is obtained from rolling experiments.
Using the total energy method proposed by Greenwood *et al.* [9] deformation friction is estimated from the following equations (for spherical and cylindrical probes).

**Cylinder:**

\[ F_c = \alpha \frac{2 W a_c}{3\pi R_c} \]  
\[ a_c = \frac{2}{\sqrt{\pi}} \left( R_c W \left( 1 - \frac{v^2}{E} \right) \right)^{\frac{1}{2}} \]

**Sphere:**

\[ F_s = \alpha \frac{3 W a_s}{16 R_s} \]
\[ a_s = \left( \frac{3}{4} R_s W \left( 1 - \frac{v^2}{E} \right) \right)^{\frac{1}{3}} \]

where \( F_c \) and \( F_s \) (N) are the rolling friction for cylinder and sphere, respectively, \( \alpha \) is the hysteresis loss for the substrate, \( W \) is the normal load (N), \( a \) (mm) is the contact radius (cylinder/sphere), \( R \) (mm) is the probe radius (cylinder/sphere), \( E \) (N/m²) is the modulus and \( v \) is the Poisson’s ratio; the units are given in the brackets.

By rearranging equation 1 and 3, all the known variables are moved to the left hand side and the unknown variables to the right hand side. This is done since the hysteresis loss and contact radius are dynamic properties of the contact which are not measured in this study. The resulting rearrangement is termed the loss-radius factor \( (lrf) \) which is a function of the hysteresis loss and contact radius (the constants \( 2/3\pi \) and \( 3/16 \) in equation 1 and 3 have been replaced with \( C \) in equation 5 and 6):

\[ (lrf)_c = \frac{F_c R_c}{W} = \alpha a_c \frac{C_c}{C} \]
\[ (lrf)_s = \frac{F_s R_s}{W} = \alpha a_s \frac{C_s}{C} \]

where, \( C \) is a constant (cylinder/sphere), \( \alpha \) is hysteresis loss factor, \( a \) is contact radius (mm).

**2.2. Calculating Adhesion and Deformation Friction**

To calculate adhesion and deformation friction, it has been assumed that rolling friction is due to hysteresis loss (deformation) and sliding is a combination of deformation
friction as well as adhesion friction. Therefore, friction (F) is given by the two term non-interacting model of friction:

\[ F = F_{adh} + F_{def} \quad (7) \]

Experimentally, deformation friction (hysteresis) is measured using rolling friction, taking the friction contribution of the bearings in the roller into account:

\[ F_{Rolling} = F_{def} + F_{Bearing} \quad (8) \]

Experimentally, sliding friction contains both deformation and adhesion friction i.e. equation 7 and 9 are equivalent.

\[ F_{Sliding} = F \quad (9) \]

where F is friction, \( F_{adh} \) is the adhesion friction, \( F_{def} \) is the deformation friction.

For the purpose of separating adhesion and deformation friction, the friction contribution due to the bearings in the rollers were measured by rolling on a stainless steel substrate for all the test conditions. Thus, the calculated values of deformation and adhesion are given by:

\[ F_{Def} = F_{Rolling} - F_{Bearing} \quad (10) \]
\[ F_{Adh} = F_{Sliding} - F_{Def} \quad (11) \]

3. EXPERIMENTAL DETAILS

3.1. Test Probes

Three probe materials were investigated namely aluminium, Noryl and PTFE in two forms i.e. spherical and cylindrical as shown in figure 3-1. The surface roughness and contact angle measurements for the probes are given in table 3-1 and figure 3-2 respectively. These probes have the common property that deformation can be assumed to be occurring entirely within the skin mimic surface i.e. \( E_{probes} >> E_{skin\ mimic} \).
Figure 3.1: Photographs of the probes, with an aluminium spherical probe on the DFI (see table 3.1 for the sizes of the probes)

Table 3.1: Probes size, material and average roughness (Ra)

<table>
<thead>
<tr>
<th>Probe Design</th>
<th>Material</th>
<th>Size</th>
<th>Average Roughness (Ra)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sphere</td>
<td>4. Polytetrafluoroethylene (PTFE)</td>
<td>Diameter: 19 mm</td>
<td>4. 1.10 µm</td>
</tr>
<tr>
<td></td>
<td>5. Noryl (polyphenylene oxide/polystyrene blend)</td>
<td></td>
<td>5. 0.45 µm</td>
</tr>
<tr>
<td></td>
<td>6. Aluminium</td>
<td></td>
<td>6. 0.41 µm</td>
</tr>
<tr>
<td>Cylinder</td>
<td>5. Polytetrafluoroethylene (PTFE)</td>
<td>Diameter: 17 mm Length: 22 mm</td>
<td>5. 0.34 µm</td>
</tr>
<tr>
<td></td>
<td>6. Noryl (polyphenylene oxide/polystyrene blend)</td>
<td></td>
<td>6. 0.19 µm</td>
</tr>
<tr>
<td></td>
<td>7. Aluminium</td>
<td></td>
<td>7. 0.50 µm</td>
</tr>
</tbody>
</table>
3.2. **Skin Mimic**

The skin mimic is a multilayer substrate that has been designed to mimic the viscoelastic behaviour and surface texture of skin. This substrate provides a consistent surface and sub-surface behaviour allowing key variables to be investigated. Table 3-2 summaries the key properties of the skin mimic:

<table>
<thead>
<tr>
<th>Property:</th>
<th>Range:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus (within the normal loads measured)</td>
<td>44-75 kPa</td>
</tr>
<tr>
<td>Average surface roughness</td>
<td>27 ± 1 µm</td>
</tr>
<tr>
<td>Contact angle</td>
<td>98 ± 5 degrees</td>
</tr>
</tbody>
</table>

The properties shown in Table 3-2 were measured on three skin mimic. Five measurements per skin mimic were carried out. The modulus range stated was based on indentation data at a rate of 3 mm/s, using a 1 mm diameter cylindrical probe. The multilayer structure of the skin mimic means that the modulus is a function of depth (indentation load) and therefore, a single modulus value is not representative. The elastic modulus range in Table 3-2 is within the range quoted in literature [7]. The average surface roughness measurements were carried out using 3D confocal microscope; the average surface roughness and the standard deviation are shown in table 3-2 and are
comparable to values for skin reported elsewhere [7]. The contact angle measurements were based on the standard sessile drop test.

3.3. Test Conditions
Table 3-3 summarises the test conditions. Two modes of operation were considered, rolling and sliding. Switching between the two modes was achieved with a pin running the length of the probes, in position it restricted movement thus achieved sliding and removing the pin allowed free rolling. Normal loads and sliding speeds were chosen to be relevant to applications in cosmetics. Three probe materials Noryl, PTFE and aluminium were investigated. The skin mimic was tested in two states, dry and lubricated. All the tests were carried out in room temperature environment.

A stroke was defined as a single non-reciprocating sliding/rolling motion along the length of the substrate for 150 mm.

Table 3-3: Summary of the test conditions

<table>
<thead>
<tr>
<th>Test Conditions</th>
<th>Property</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal load:</td>
<td>Sphere: 0.7 -1.45 N</td>
</tr>
<tr>
<td></td>
<td>Cylinder: 1.0 - 3.0 N</td>
</tr>
<tr>
<td>Sliding Speed:</td>
<td>10, 50, 100, 200, 250, 300 (mm/s)</td>
</tr>
<tr>
<td>Probe Material:</td>
<td>Noryl (polyphenylene oxide/polystyrene blend), PTFE and aluminium</td>
</tr>
<tr>
<td>Lubrication:</td>
<td>Dry and Lubricated (Newtonian oil: Viscosity 0.3 Pa.s)</td>
</tr>
<tr>
<td>Stroke Length:</td>
<td>150 mm</td>
</tr>
</tbody>
</table>

3.4. Test Procedure
The five parameters investigated were probe geometry, probe material, normal load, sliding speed and lubrication. This gives a total of 180 combinations for sliding and 180 combinations for rolling. Each test combination was repeated three times. All the test conditions were carried out on the same skin mimic and the dry tests were carried out before the lubricated tests. For the lubricated conditions, the oil was spread manually on the surface and reapplied for each condition.
3.5. Dynamic Friction Instrument (DFI) and Data Analysis

This study utilised the DFI in conjunction with another system composed of a robotic arm that provided consistent sliding speed and normal load. The two systems complement one another; the DFI measured friction while the robotic arm maintained sliding speed and normal load. The errors in the measured values of normal load and friction are given in Table 3-4 and apply to all the data presented in section 4.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal load</td>
<td>+/- 0.5 %</td>
</tr>
<tr>
<td>Friction</td>
<td>+/- 1.0 %</td>
</tr>
</tbody>
</table>

Each test condition was analysed by considering only the dynamic friction. This is done by taking a subset of the stroke in the region where the friction is relatively stable (coloured regions in figure 3-3). An example of a set of three strokes is shown in figure 3-3. The three strokes are averaged and represent a single friction data point in figures shown in section 4.

Figure 3-3: Example stroke profiles. Friction as a function of time for three strokes (aluminium speed 10 mm/s, normal load 2.2 N). The coloured regions represent the subset taken to be the dynamic friction.
4. RESULTS/DISCUSSION

4.1. Overview
The deformation and adhesion data are presented in two formats. Section 4.2 and 4.3 present the data in friction as function of speed, while section 4.4 presents the oil data in a Stribeck curve. Section 4.5 presents the data in terms of relative contribution of adhesion and deformation to total friction as function of speed.

4.2. Deformation Friction (dry/lubricated)
Figures 4.1 and 4.2 show deformation friction as a function of speed at three different normal loads, representing all the materials tested (aluminium, PTFE and Noryl). Each data point is an average taken from all three materials and calculated using equation 10. Further, lubricating the surface has negligible effect on deformation friction (hysteresis). This is indicative of pure rolling where probe material and lubrication have little effect on the measured hysteresis friction [8]. This has an important implication when calculating adhesion friction for dry and lubricated contacts, since the same deformation value can be assumed to be present in both cases.

![Figure 4-1: Deformation friction as a function of speed for the cylindrical probes at three normal loads (each data point is an average of aluminium, Noryl and PTFE).](image-url)
Figure 4-2: Deformation Friction as a function of speed for the spherical probes at three normal loads (each data point is an average of aluminium, Noryl and PTFE).

The data shows that for the cylindrical and spherical probes, the deformation friction increases with increasing normal load and sliding speed. Pioneering work by Grosch on rubber showed sliding friction increases with speed and this was related to the material’s loss tangent. It was shown that the maximum friction coincided with the maximum values of the loss modulus [12]. In this study, this relationship was not investigated but rather the loss-radius factor is used to explore the change of deformation friction with sliding speed.

To isolate the effect of speed on the loss-radius factor \((lrf)\), the effect of normal load is factored out from the right hand side of equations 5 and 6 to give what is termed as the modified loss radius factor shown in equations 12 and 13. This is achieved by plotting loss-radius factor \((lrf)\) as a function of normal load and finding the normal load dependence. The empirically modified loss-radius equations for cylinder and sphere are:

\[
(lrf)_{cm} = \frac{(lrf)_c}{w^\sigma} = F_c \frac{R_c}{w^\sigma} = \alpha a_{cm} c_c \quad (12)
\]

\[
(lrf)_{sm} = \frac{(lrf)_s}{w^{10}} = F_s \frac{R_s}{w^{10}} = \alpha a_{sm} c_s \quad (13)
\]
where \((lrf)_{cm}\) is the modified loss factor for cylinder \((\text{mm/N}^{(1/5)})\), \((lrf)_{sm}\) is the modified loss factor for sphere \((\text{mm/N}^{(1/10)})\), \(a_{cm}\) is the modified contact radius for cylinder and \(a_{sm}\) is the modified contact radius for sphere.

The contribution of normal load to the loss-radius factor is \(\sim W^{1/5}\) for the cylindrical probe while for the spherical probe it is \(\sim W^{1/10}\). Figures 6 and 7 show that the modified loss-radius factors varies as a function of speed for both the cylindrical and spherical probes, supporting the hypothesis that deformation is a function of speed for a given normal load [11]. Since the loss-radius factor consists of a constant, hysteresis loss and radius, figure 4-3 and 4-4 indicate the increase of deformation friction with speed is due primarily to the combined effect of increasing hysteresis loss and radius with increasing speed.

![Figure 4-3: Modified loss-radius factor as a function of speed for the cylindrical probe](image-url)

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Comparing the present work to other published data, Johnson et al estimated deformation friction using equation 1 and obtained a coefficient of friction of 0.05 at a normal load of 0.2 N [13]. Experimentally, Adams et al measured deformation friction using rolling and found a coefficient of friction of 0.04 at a normal of 0.2 N at a maximum rolling speed of 50 mm/s [2]. In the present study, higher sliding speeds and normal loads were used giving a coefficient of friction in the range of 0.1-0.22.

4.3. **Adhesion Friction (dry)**
Figure 4-5: Adhesion Friction as a function of speed for the Aluminium Cylindrical probe in the dry state

Figure 4-6: Adhesion Friction as a function of Speed for the Aluminium Spherical Probe in the dry state

Figure 4-5 and 4-6 show adhesion friction for the cylindrical and spherical probes in the dry state based on equation 11. The results show that for speeds greater than 50 mm/s, adhesion friction is a constant. The variation below 50 mm/s is primarily attributed to the method used to estimate adhesion friction where the interaction at the lower speeds is not independent of deformation friction.

The adhesion curves for PTFE and Noryl probes show similar trends to that of aluminium where at low speeds (below 50 mm/s) adhesion friction varies with speed but further increase in speed results in a constant value in adhesion friction.

PTFE had the lowest overall adhesion friction, followed by Noryl with aluminium having the highest adhesion friction. Water contact angle measurements were carried out (figure 3-2) and this correlated with adhesion friction measured for the three probe materials. If water contact angle is indicative of surface energy, then the results show increasing surface energy increases adhesion friction.

Friction is a system property and as a result, the conditions around each measurement are important, if the values of the coefficient of friction are to have any meaning. Reported values of coefficient of friction of skin have ranged from around 0.1 on the abdomen using
a Teflon probe to around 3 on the hands on different rock surfaces [14]. In the present study, the coefficient of friction (adhesion friction) ranged between 0.4 - 1.1.

4.4. Adhesion Friction (lubricated)
The oil data have been presented using a Striebeck curve to understand the lubrication regime for the conditions tested. The primary reason for this is the complex relationship between friction, speed and normal load, which make the interpretation of the data difficult, if presented in the same format as the dry data.

![Striebeck Curve](image)

**Figure 4-7:** Data show coefficient of friction as a function of the Striebeck number for the aluminium cylindrical probe (log-log scale). (Striebeck number: (Velocity (mm/s) * viscosity (Pa.s)) / normal load (N))

Figure 4-7 shows the Striebeck curve of adhesion friction for the cylindrical aluminium probe. The coefficient of friction values observed (minimum value around 0.2) suggest that the prevailing lubrication mechanism is boundary lubrication as hydrodynamic lubrication would be associated with much lower friction co-efficients. Similar results are seen for the remaining two materials (PTFE and Noryl) and probe geometries (sphere and cylinder) where they are all in the boundary lubrication regime. The viscosity of the oil used in this study was 0.3 Pa.s, this is comparatively higher than sebum and sweat which have viscosities of 0.086 [15] and 0.0009-0.0012 Pa.s [16] at 30 degree Celsius respectively.
4.5. **Percentage Contribution to Total Friction**

Figure 4-8 and 4-9 show the percentage contribution to total friction for the cylindrical aluminium and spherical probes respectively. Deformation friction contributes 10% at the lower speeds and increases to a constant of 20% at higher speeds. This trend is seen for both cylindrical and spherical probes in the normal load range considered. For the range of normal loads and the two geometries tested appear to have no effect on the relative proportions of adhesion and deformation friction. As already noted, the effect of speed especially at the lower range is attributed to the method used to separate adhesion and deformation and the assumption that they are independent. The effect of material on the relative contribution is evident with PTFE, which had the lowest adhesion friction. This results in a greater relative contribution of deformation friction as high as 30% at high speeds (figure 4-10).

![Figure 4-8: Percentage contribution to Total Friction as a function of speed for the dry cylindrical aluminium probe](image-url)
Figure 4-9: Percentage contribution to Total Friction as a function of speed for the dry spherical aluminium probe

Figure 4-10: Percentage contribution to Total Friction as a function of speed for the dry cylindrical PTFE probe
The relative contribution to total friction significantly changes in the presence of a lubricant. Since the contribution of deformation friction remains the same irrespective of lubrication, it contributes a greater proportion to the total friction. Figure 4-11 shows deformation friction for the cylindrical probe where deformation friction contributes as much as 50% of the total friction for high normal loads and speeds. This signifies the importance of considering deformation friction in applications where normal loads and speeds are high. Similar results are seen for PTFE and Noryl materials (cylinder and sphere), where the relative proportion of deformation friction increase similar to the result of figure 4-11.

5. CONCLUSION
This study has set out to understand the relative contribution of adhesion and deformation to total friction using a deformable multi-layer substrate that mimics the viscoelastic behaviour and surface texture of skin.

The five parameters investigated were: probe geometry, probe material, normal load, speed and lubrication. This study draws the following observations:
• The impact of the probe geometry on the relative contributions of adhesion and deformation is negligible for both the dry and lubricated states.

• Probe material does affect the relative contribution of adhesion and deformation in the dry state; 20% of the total friction for aluminium and Noryl is due to deformation friction and this increases to 30% for PTFE. In the lubricated state the probe material does not seem to be significant.

• In the range tested, normal load has negligible effect on the relative proportion of adhesion and deformation friction in the dry state. In the lubricated state, the relative proportion of adhesion and deformation are affected by normal load in conjunction with speed.

• In dry the state, the effect of speed and normal load on the relative proportions of adhesion and deformation is negligible. For the lubricated state, increasing speed and normal load results in the relative proportions of adhesion and deformation to approach 50/50. This has significant practical importance for applications where relatively high normal loads and speeds are used on skin, implying deformation friction should not be ignored.

In conclusion, deformation friction contributes a relatively significant proportional to total friction for dry and lubricated contact (especially in conditions where relatively high normal loads and speeds are being applied).

ACKNOWLEDGEMENTS

The research was funded by Engineering and Physical Science Research Council (EPSRC) through the University of Surrey EngD Centre and Proctor and Gamble (P&G). Grant reference number: EP/G037388/1

REFERENCE


