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

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ABSTRACT

This study is concerned with determining the relative contribution of adhesion and deformation friction using rolling and sliding method. 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.

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 (Fig. 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.

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 3 covers the experimental details. Section 4 presents the results and discussion. Section 5 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

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Notation

α	hysteresis loss
$(lrf)_c$	loss-radius factor (cylinder)
$(lrf)_s$	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
R_s	sphere radius

Units

$(lrf)_c$	mm
$(lrf)_s$	mm
$(lrf)_{cm}$	$(\mathrm{mm/N}^{(1/5)})$
$(lrf)_{sm}$	$\mathrm{mm/N}^{(1/10)}$

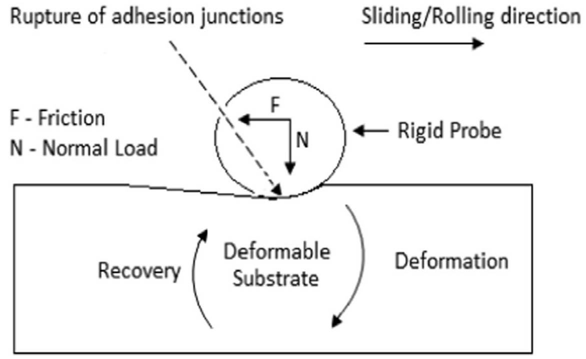

Fig. 1. Schematic diagram of probe—substrate interaction (adapted from [2]).

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).

$$\textbf{Cylinder}: F_c = \alpha \frac{2}{3\pi} \frac{W a_c}{R_c} \tag{1}$$

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

$$\textbf{Sphere}: F_s = \alpha \frac{3}{16} \frac{W a_s}{R_s} \tag{3}$$

$$a_s = \left(\frac{3}{4} R_s W \frac{1-\nu^2}{E} \right)^{\frac{1}{3}} \tag{4}$$

where F_c and F_s (N) are the rolling friction for cylinder and sphere, respectively, α 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/m^2) is the modulus and ν is the Poisson's ratio; the units are given in the brackets.

By rearranging Eqs. (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 Eqs. (1) and (3) have been replaced with C in Eqs. (5) and (6)):

$$(lrf)_c = \frac{F_c R_c}{W} = \alpha\, a_c\, C_c \tag{5}$$

$$(lrf)_s = \frac{F_s R_s}{W} = \alpha\, a_s\, C_s \tag{6}$$

where C is a constant (cylinder/sphere), α 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:

$$F = F_{\text{adh}} + F_{\text{def}} \tag{7}$$

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

$$F_{\text{Rolling}} = F_{\text{def}} + F_{\text{Bearing}} \tag{8}$$

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

$$F_{\text{Sliding}} = F \tag{9}$$

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

$$F_{\text{Def}} = F_{\text{Rolling}} - F_{\text{Bearing}} \tag{10}$$

$$F_{\text{Adh}} = F_{\text{Sliding}} - F_{\text{Def}} \tag{11}$$

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 Fig. 2. The surface roughness and contact angle measurements for the probes are given in Table 1 and Fig. 3, respectively. These probes have the common property that deformation can be assumed to be occurring entirely within the skin mimic surface i.e. $E_{\text{probes}} \gg E_{\text{skin mimic}}$.