Tribology International 89 (2015) 119–127

Contents lists available at ScienceDirect

Tribology International

journal homepage: www.elsevier.com/locate/triboint

Friction mechanisms and abrasion of the human finger pad in contact with rough surfaces

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ARTICLE INFO

Article history:
Received 5 August 2014
Received in revised form
13 December 2014
Accepted 24 December 2014
Available online 2 January 2015

Keywords:
Skin tribology
Finger pad
Friction mechanisms
Ploughing and abrasion

ABSTRACT

The friction and abrasion behaviour of the finger pad on abrasive papers was investigated in friction experiments, combined with microscopic analyses and a protein assay to quantify skin particles abraded in friction contacts. Friction measurements at varied normal forces resulted in relatively high and load-independent friction coefficients, pointing to ploughing and abrasion as important friction mechanisms. The microscopic analyses revealed that large numbers of skin particles are abraded in form of single corneocytes, corneocyte fragments and agglomerates of corneocytes. In addition, micro-scratches were observed on the epidermal ridges of the finger pad after friction contacts. In friction measurements at the same conditions, the amount of abraded skin particles varied for abrasive papers with different roughness, while friction coefficients were comparable.

1. Introduction

The hands and fingers of humans are crucial for interacting with the environment, be it when grasping and handling objects and tools or during tactile and haptic experiences with materials and surfaces. Mechanical interactions between fingers and objects as well as tactile perception essentially rely on the properties and functions of the human skin. In recent review articles, the contact and friction behaviour of the finger pad was discussed specifically [1,2] and in comparison with the skin of other body areas [3]. The friction behaviour of the finger pad largely corresponds to that of human skin in general and at the same time is influenced by specific anatomical and physiological factors.

Important characteristics of the hairless skin of the finger pad are (1) a relatively thick epidermis (~0.5 mm), (2) the fingerprint pattern on the surface and (3) a high density of sweat glands (up to 400 per cm^2) [4,5]. An additional aspect is that the skin and the subcutaneous soft tissue are mechanically stabilised and confined by the distal phalanx and the finger nail, leading to a pronounced non-linear deformation behaviour during mechanical contacts [6]. There is evidence that the epidermal surface ridges serve to improve tactile perception by amplifying vibrational stimuli for the mechanoreceptors located in the subsurface skin tissue [7,8]. At the same time, the ridged skin surface has an influence on the friction behaviour of finger pads, as the surface pattern decreases the skin contact area against a smooth counter-surface to about 30% of the apparent contact area [9] and is likely to cause interlocking effects when in contact with the asperities of a rough counter-surface [10,11]. The skin-material interface is strongly influenced by skin hydration and interfacial water due to sweating. It is believed that hydration and moistening swell and soften the stratum corneum and facilitate capillary bridges, so that the contact area and the adhesion against a counter-surface are increased [12–14]. The friction coefficient of the finger pad assumes a maximum in the moist condition, while being considerably lower under dry and completely wet conditions [12,13,15].

The friction behaviour of human skin is commonly described by the two-term model of friction, implying that the total friction is the sum of two independent contributions due to adhesion and deformation, respectively [3,16]. The deformation component is usually much smaller than the adhesion component [16,17], but under specific conditions the contribution of deformation has been found to be significant, e.g. for wet skin in contact with rough surfaces [18,19] or for the finger pad sliding on ridged surfaces [10,20]. The origin of the deformation component often remains unclear, because different mechanisms such as ploughing, viscoelastic hysteresis and interlocking can be involved. A further open question is, to what degree skin is abraded in friction contacts with rough surfaces and how skin abrasion contributes as a possible additional term to the total friction,

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http://dx.doi.org/10.1016/j.triboint.2014.12.023
0301-679X/

similar to the cohesion component of friction known for rubber and elastomers [21].

The objective of the present study was to gain new insights into the deformation component of the friction of human skin (finger pad) on rough surfaces by identifying and analysing the involved friction mechanisms. In particular, the abrasion of skin resulting in friction contacts was quantitatively determined in order to investigate whether skin abrasion leads to a systematic contribution to the measured friction coefficient.

2. Methods

2.1. General

Measurements of the friction between the finger pad and different rough surfaces were combined with microscopic and biochemical analyses, in which the abrasion of skin occurring in friction contacts was quantified. The parameters and conditions of the friction measurements were held constant as far as possible in order to ensure high repeatability. As skin hydration is known to have an important influence on friction, this parameter was closely monitored during the experiments. The study was approved by the ethics committee of the canton St. Gallen, Switzerland (Ref. Nr. EKSG 14/001).

2.2. Materials

Two reference glass surfaces and three different abrasive papers (SiC) with grit sizes of 600, 800, and 1200 were used as counter-materials for the finger pad in the friction experiments. The surfaces of the abrasive papers ranged from fine to very fine and were characterised by grains with diameters of 25.8 ± 1 μm, 21.8 ± 1 μm, and 15.3 ± 1 μm, respectively. The selection of the materials was based on pre-tests, in which the feasibility of in vivo friction measurement series with negligible skin injury risk was verified. Surface roughness parameters of the materials were measured using a mechanical profilometer (Perthometer M1, Mahr GmbH, Göttingen, Germany). Table 1 shows results for the arithmetic average height (Ra), the average peak-to-valley height (Rz), and the maximum height of the profile (Rmax) [22]. The roughness parameters of the abrasive paper with grit size 1200 were comparable with those of the rough glass reference surface, while the other abrasive papers were rougher.

2.3. Friction and skin hydration measurements

All friction experiments were carried out by the same subject (male, 25 years old), thereby using the index finger of the left hand. The experimental set-up for friction measurements was similar as described in previous studies [6,18,23]. In brief, materials (Section 2.2) were attached on a tri-axial force plate (Kistler, Type 9254, Winterthur, Switzerland) to measure the tangential and normal forces during friction contacts with the finger pad and to determine friction coefficients (Fig. 1). The subject repeatedly rubbed the finger over a distance of 40 mm on the surface to be investigated (pulling motion of the finger towards the body). The sliding velocity of the finger, determined via the duration of friction contacts, was 45 ± 8 mm/s. Friction coefficients were determined from the middle third of each sliding friction contact. During an individual friction measurement the index finger was held in a stretched, flat position close to the horizontal. After each stroke, the hydration of the skin was measured with a Corneometer (CM 825, Courage & Khazaka, Cologne, Germany), indicating the hydration state in arbitrary units ranging from 0 to 120 (CM value).

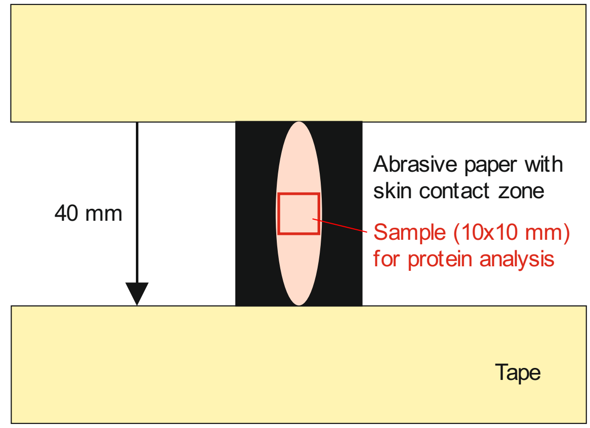

Fig. 1. Schematic drawing of the force plate with a sample of abrasive paper attached. After friction measurements, a square sample of the abrasive paper is taken from the middle of the skin contact zone in order to analyse the amount of abraded skin particles.

Table 1
Results for standard roughness parameters of the glass reference surfaces and abrasive papers with different grit sizes. Mean values ± standard deviations of 10 measurements, 5 in each of two orthogonal directions. In case of smooth glass upper limits are reported, as the measured results were close to the resolution of the measurement device.

Material	Ra [μm]	Rz [μm]	Rmax [μm]
Glass smooth	< 0.015	< 0.030	< 0.040
Glass rough	5.0 ± 0.3	26.4 ± 1.3	34.5 ± 3.9
Abrasive paper 1200	4.4 ± 0.3	26.5 ± 1.8	31.4 ± 2.5
Abrasive paper 800	6.4 ± 0.3	36.7 ± 1.6	41.7 ± 1.5
Abrasive paper 600	8.1 ± 0.7	44.9 ± 2.7	52.1 ± 6.1

The experiments took place in a laboratory with a temperature of 23 ± 3 °C and a relative humidity of 50 ± 5%. After entering the room, the subject washed his hands with water and acclimatised to the laboratory conditions for at least 15 minutes prior to the first measurement. A single measurement series comprised a sequence of 5 to 6 individual sliding friction contacts between the finger pad and a counter-surface within a period of 30 s. Two different load configurations were used in measurement series: In the first configuration, constant normal forces of about 2 N were applied by the finger, while in the second the normal forces were randomly varied between about 0.1 N and 5 N. For each surface type and load configuration, 10 measurement series were repeated. When measuring friction coefficients on abrasive papers at different loads, only 4 measurement series were carried out in order to avoid extensive wear of the finger skin. The intactness of the finger pad skin was regularly checked by means of surface replica produced before and after friction measurement series, see below. In the case of the abrasive papers, new material samples were used for each measurement series. The glass surfaces were cleaned with ethanol before each measurement series.

It is known that the renewal time of the stratum corneum is approximately 14 days after skin damage or shedding of the skin [4,24]. Therefore, regeneration periods were scheduled during the course of the experiments.

2.4. Microscopic analyses

The skin particles abraded in friction contacts with rough surfaces were investigated by means of a digital optical microscope (Keyence VHX-1000, Osaka, Japan) and scanning electron microscopy (Hitachi S-4800, Hitachi High-Technologies US and Canada, Illinois, USA). Skin particles abraded or deposited on the counter-surfaces were collected by the application and removal of an adhesive tape (Corneofix®, CKelectronic, Cologne, Germany) for subsequent microscopic analyses. In the case of the abrasive