ARTICLE IN PRESS

Biotribology xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Biotribology

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

Feeling fine - the effect of topography and friction on perceived roughness and slipperiness

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ARTICLE INFO

Keywords:
Tactile perception
Roughness
Slipperiness
Friction

ABSTRACT

(1) Background. To design materials with specific haptic qualities, it is important to understand both the contribution of physical attributes from the surfaces of the materials and the perceptions that are involved in the haptic interaction. (2) Methods. A series of 16 wrinkled surfaces consisting of two similar materials of different elastic modulus and 8 different wrinkle wavelengths were characterized in terms of surface roughness and *tactile friction* coefficient. Sixteen participants scaled the perceived Roughness and Slipperiness of the surfaces using free magnitude estimation. Friction experiments were performed both by participants and by a trained experimenter with higher control. (3) Results and discussion. The trends in friction properties were similar for the group of participants performing the friction measurements in an uncontrolled way and the experiments performed under well-defined conditions, showing that the latter type of measurements represent the general friction properties well. The results point to slipperiness as the key perception dimension for textures below 100 μm and roughness above 100 μm. Furthermore, it is apparent that roughness and slipperiness perception of these types of structures are not independent. The friction is related to contact area between finger and material. Somewhat surprising was that the material with the higher elastic modulus was perceived as more slippery. A concluding finding was that the flat (high friction) reference surfaces were scaled as rough, supporting the theory that perceived roughness itself is a multidimensional construct with both surface roughness and friction components.

1. Introduction

Tactile perception is considered an important contributor to the overall experience of products such as packaging, magazines, fabrics, skin and hair care products and tactile displays. Predictive capacity of how new products or modifications of existing products will be tactually perceived by the customer or end user, would facilitate product development and make it more cost-effective, due to a more systematic product design with less trial and error. Thus, an understanding of how process parameters, material and surface properties (e.g. surface roughness, thermal conductivity and diffusivity) and interfacial phenomena such as friction affect the perceptual response is of importance.

Active exploration of a surface with a human hand is really a tribological event and consequently the tactile interest has increased rapidly over the last years within the field of tribology [1–3]. The friction that arises during active exploration at the finger-surface interface is sometimes called tactile friction [3–5]. From a perception perspective it is preferable to mimic the haptic interrogation process by moving the finger over a stationary surface placed on a force cell device [2,6–17]. The skin friction and skin mechanics of this situation has recently been reviewed [3,18,19]. The friction response is highly affected by various properties such as finger hydration [5,7,17,20,21] and surface roughness [4,5,7,22,23]. Typically friction decreases with increasing surface roughness at the small scale and the trend reverses at higher roughness. A common feature of skin friction studies is the variation in the response between different participants, which is often associated with variations in skin moisture content [20,22,24,25]. While skin friction has been addressed extensively, less effort has been made to combine tactile friction measurements and surface properties with perceptual evaluation, i.e. measurements with human subjects. Derler and Gerhard [19] observed that tactile perception and haptics in relation to skin tribology is largely unstudied and poorly understood. Liu et al. [26] correlated tactile friction and surface roughness with the rough-smooth and grippy-slippery perceptions on car seat materials and Barnes et al. [27] found that glass surfaces were perceived pleasant or desirable once the surface was less rough than the fingertip. Chen et al. [28]

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http://dx.doi.org/10.1016/j.biotri.2017.01.002
Received 31 October 2016; Received in revised form 20 January 2017; Accepted 30 January 2017
2352-5738/

Table 1
Properties of the model surfaces. The wavelength (λ) and amplitude (A) before and after use in friction and perception studies was measured by profilometry. The preparation parameters - stretch distance and UVO irradiation time- are also given.

ID	λ_{before} (μm)	A_{before} (μm)	Material	Prep. method	Prep. settings	λ_{after} (μm)	A_{after} (μm)
S1	–	–	NOA 73	None, reference	–	–	–
S2	–	–	NOA 81	None, reference	–	–	–
S3	30.5 ± 0.5	1.7 ± 0.1	NOA 73	Wrinkling	50%, 80 min	30.4 ± 0.8	1.6 ± 0.1
S4	30.5 ± 0.8	1.7 ± 0.1	NOA 81	Wrinkling	50%, 80 min	30.5 ± 0.8	1.6 ± 0.03
S5	42.5 ± 0.4	3.4 ± 0.3	NOA 73	Wrinkling	30%, 120 min	42.5 ± 0.4	3.4 ± 0.2
S6	42.6 ± 0.3	3.6 ± 0.3	NOA 81	Wrinkling	30%, 120 min	42.9 ± 0.3	3.6 ± 0.3
S7	52.0 ± 2.7	4.0 ± 0.4	NOA 73	Wrinkling	40%, 160 min	50.3 ± 1.6	4.0 ± 0.4
S8	50.2 ± 1.4	4.1 ± 0.3	NOA 81	Wrinkling	40%, 160 min	52.5 ± 4.6	3.8 ± 0.7
S9	58.4 ± 1.7	6.8 ± 0.5	NOA 73	Wrinkling	50%, 160 min	58.0 ± 2.6	6.6 ± 0.4
S10	58.2 ± 1.9	7.3 ± 0.1	NOA 81	Wrinkling	50%, 160 min	58.6 ± 2.2	7.1 ± 0.1
S11	79.4 ± 1.5	8.0 ± 0.4	NOA 73	Wrinkling	30%, 240 min	79.1 ± 0.9	8.1 ± 0.1
S12	79.0 ± 2.3	8.4 ± 0.4	NOA 81	Wrinkling	30%, 240 min	79.1 ± 1.4	8.3 ± 0.3
S13	96.1 ± 0.6	7.3 ± 0.3	NOA 73	Wrinkling	20%, 300 min	95.7 ± 0.7	6.8 ± 0.7
S14	96.2 ± 1.3	6.4 ± 0.7	NOA 81	Wrinkling	20%, 300 min	96.7 ± 0.1	6.2 ± 1.0
S15	n.a.*	n.a.*	NOA 73	3D-printing	–	130 ± 15.6	46.6 ± 5.4
S16	118 ± 17	47 ± 6	NOA 81	3D-printing	–	112 ± 6.2	47.0 ± 2.6

*Faulty measurements discovered after the perception experiment, thus not possible to redo as a before measurements.

investigated relations between touch perceptions of different cardboards and physical measurements. Questionnaires of warmth-cold, slippery-sticky, smooth-rough, hard-soft, bumpy-flat and wet-dry were linked with physical measurements of surface roughness, compressibility, friction and the rate of cooling and the touch perception was to be associated with more than one physical property. Chen et al. [29] also investigated relationships between the affective and sensorial judgments and the various physical measurements and concluded that further work is needed, particularly to quantify roughness and sliding friction in a manner useful for relating to the affective responses.

In order to get a more comprehensive picture of tactile perception, researchers have tried to map the dimensions of the tactile space using multidimensional scaling [30–35]. Texture perception is generally found to be 3-dimensional with a roughness-smoothness, softness-hardness, and a stickiness-slipperiness dimension [30,31,33]. The dimensionality has also been found to be similar in micro-textures with structures below 100 μm [36,37].

The sense of touch is quite remarkable in detecting small textural variations. Single asperities down to at least 1 μm can be detected [38] and applying a repeated wave pattern with an amplitude of approximately 10 nm is enough to change the perception from that of a smooth surface with otherwise identical chemistry [10]. Texture perception has attracted a lot of attention in recent years and the majority of effort has focused on roughness, e.g. [39]. While roughness of coarse surfaces is relatively well understood, the same cannot be said for roughness of finer surfaces. There are different theories of how the neural coding of roughness of fine textures work. Some propose a spatial (SA1) model for roughness coding [40–42] where SA1 afferents code roughness for all textures. Others propose a duplex theory where SA1 afferents code roughness above 200 μm and Pacinian corpuscles (PC) below 200 μm, through vibrations, [33,43,44], both with compelling arguments. It has also been proposed that spatial information was retrievable well below the postulated limit for the SA1 afferents, through vibrations [10,45]. This notion was given some support by Weber et al. [46] who found that both temporal and spatial codes through Rapidly Adapting (RA) and PC afferents were indeed used in haptic perception of micro-textures, this idea was further elaborated on by Saal and Bensmaïa [47]. As spatial information gets more difficult to rely on, vibrations and friction become more significant in texture perception. Though *slipperiness* is much less studied than *roughness* [39], friction has been found to be the main physical property associated with slipperiness perception, e.g. [48]. In a recent study on haptic perception of micro-textures, two dimensions were found to be sufficient to explain the similarities in 0–80 μm wavelength surfaces and were identified with the physical parameters of friction and wavelength [10]. What was *not* clear from that study was the relationship between slipperiness and roughness. Here we have thus examined the relationship between perceived roughness and perceived slipperiness as well as the psychophysical relationship with friction and topography for micro-textures.

2. Materials and methods

2.1. Fabrication and characterisation of wrinkle-patterned surfaces

Model surfaces with controlled texture were prepared by surface wrinkling or 3D–printing. The surface wrinkling procedure, used to obtain structures in the wavelength region 30–100 μm, has been described in detail previously [10,49,50]. In brief, polydimethylsiloxane (PDMS, Sylgard 184 Dow Corning, USA) was stretched and then exposed to ultraviolet ozone (UVO) (UV/Ozone ProCleaner, Bioforce Nanosciences), oxidizing a thin overlayer of the PDMS into a stiffer film with higher elastic modulus than the rest of the substrate. When the strain was released surface wrinkles formed spontaneously due to the difference in elastic modulus between the layers [50]. By altering the stretch distance (% increase compared to the original substrate) and UVO exposure time the desired structures were obtained, as summarized in Table 1. Surfaces with wavelengths above 100 μm were obtained by 3D-printing (3D-Intelligence, Grästorp, Sweden) on VeroClear-RGD810 (an acrylic based photopolymer) followed by replication onto PDMS. Each structured PDMS-substrate was then replicated onto less