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Short communication

Sticky fingers: Adhesive properties of human fingertips

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ABSTRACT

Fingertip friction is a rather well studied subject. Although the phenomenon of finger stickiness is known as well, the pull-off force and the adhesive strength of human finger tips have never been previously quantified. For the first time, we provided here characterization of adhesive properties of human fingers under natural conditions. Human fingers can generate a maximum adhesive force of 15 mN on a smooth surface of epoxy resin. A weak correlation of the adhesive force and the normal force was found on all test surfaces. Up to 300 mN load, an increase of the normal force leads to an increase of the adhesive force. On rough surfaces, the adhesive strength is significantly reduced. Our data collected from untreated hands give also an impression of an enormous scattering of digital adhesion depending on a large set of inter-subject variability and time-dependent individual factors (skin texture, moisture level, perspiration). The wide inter- and intra-individual range of digital adhesion should be considered in developing of technical and medical products.

1. Introduction

The understanding of mechanical properties of human fingertips is of great importance for various scientific disciplines. The fingertip adhesion is a significant parameter in the development and improvement process of medical products and manual interfaces of technical devices. Although everybody knows the phenomenon of sticky fingertips occurring after pressing a finger against a smooth surface, up to now the perpendicular adhesive force of human fingertips has never been quantified by experimental data. Pailler-Mattéi and Zahouani, (2006) and Pailler-Mattéi et al. (2007) analyzed the adhesive properties of human skin by indentation tests, but their measurements were carried out at the inner forearm, not on digital pads. Since microstructure, moisture content, and mechanical properties of different skin areas are very different, these published data cannot be directly taken to understand fingertip adhesion. Among the large number of publications on frictional properties of human skin (reviewed in Tomlinson et al., 2007; Derler and Gerhardt, 2012; Van der Heide et al., 2013), experiments on human skin suggest that adhesion may be a strong factor contributing to friction forces (Wolfram, 1983; Adams et al., 2007; Kwiatkowska et al., 2009). During the sliding process, temporary junctions, caused by intermolecular adhesive forces, have to be ruptured, which potentially leads to stick–slip motion. However, also these studies provide no information on the range of adhesive forces occurring, when a finger tip detaches from a surface.

The goal of this study was to evaluate the amount of adhesive strength of human fingers under natural conditions. We quantified the adhesive force of the index finger and the thumb on surfaces having same chemistry, but different texture profiles. Measurements made under a wide range of load conditions aided in drawing a comprehensive image of the controllability of adhesion by the grasping strength.

2. Material and methods

Adhesive forces of the volar pads of the tips (Phalanx distalis) of the left hand's index finger (Digitus secundus) and the thumb (Pollex) were measured in five female and five male test persons (24–32 years) under varying normal load ranging from 0 to 1N at $T=19.9$–21.3 °C and RH=27.7–38.6% on four substrates: a smooth microscopy slide (Carl Roth GmbH & Co. KG, Karlsruhe, Germany), two polish papers of 1 and 12 μm grain size (FiberMet® Abrasive Discs, Buehler, Illinois, USA) and a sand paper P320 (Carbo Schröder, Hannover, Germany). In order to exclude the influence of material-specific surface chemistry, resin replicas of these substrates were made. A polyvinylsiloxane (PVS) polymer negative (AFFINIS®, light body, ISO 4823, Type 3, low consistency, Coltène/Whaledent AG, Altstätten, Schwitzerland) of 2.56 cm² of each substrate was made and repeatedly filled with 1 g of fluid epoxy resin with a mixture ratio of ERL=10.0, D.E.R=6.0, NSA=26.0, and DMAE=0.4 (see Spurr, 1969). The polymerised resin had a Young´s modulus of 7 GPa (Peisker and Gorb, 2010). The grain size of the test surfaces was determined from 60 grains of three scanning electron micrographs by using the software ImageJ (Version 1.43 u, Wayne Rasband, National Institutes of Health, USA). Therefore, samples of all surfaces were sputter coated with a 10 nm layer of gold palladium (Leica SCD500, Leica Microsystems GmbH, Wetzlar, Germany) and subsequently examined in the SEM HITACHI S4800 (Hitachi High-Technologies Corporation, Tokyo, Japan). The sand paper P320 had a grain size of 55.3 ± 14.98 μm (manufacturer's information: 46.2 ± 1.5 μm). The polish paper of

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1 μm and 12 μm had a grain size of 1.3 ± 0.54 and 10.8 ± 4.1 μm and an average roughness (Ra) of 0.38 ± 0.05 μm and 3.39 ± 1.02 μm and a root mean squared roughness (RMS) of 0.47 ± 0.06 μm and 4.16 ± 0.97 μm (data from Spinner et al., 2014).

For the adhesion measurements a 100 g force sensor (World Precision Instruments, Inc, Sarasota, USA) connected with a *BIOPAC System* (System and software Acq*Knowledge*® Version 3.7.3, BIOPAC Systems Inc, Santa Barbara, USA) was equipped with one of the test surfaces and tapped shortly in a vertical direction (down to the finger pad oriented upwards) with the underside of the apical digital pads and thereafter pulled off again. The test persons did not wash their hands at least one hour before the experiment. Continuous detection of forces, acting on the sensor, allowed to quantify the normal forces between the finger and the test surface, as well as to record the adhesive forces during the detachment process (Supplementary Fig. 1). The different test surfaces were pressed for 1.5 s against the finger with varying normal force for a time period of 60 s with as many repetitions as possible. The four test surfaces were changed in a random order so that each surface roughness was tested four times. For each test person, a new set of test surfaces was produced. The individual force measurements (= curves) were analyzed separately: The normal load was defined as the difference between the curve maximum and the offset defined by the noise level (Supplementary Fig. 1). Fingertip adhesion was in turn defined as difference between the curve minimum and the noise level (Supplementary Fig. 1). The level of noise was determined by calculation of the mean values of 200 data points (400 ms) before the sensor was pressed against the fingertip (Supplementary Fig. 1). The lowest value for the adhesive forces, taken into account in our subsequent analysis, depended on the mean value of noise and was about 2.8 mN. A total number of 3200 measurements was analyzed. The final data set included 320 curves per test person (resulting from four measurements with ten repetitions at the thumb and the index finger on each test surface).

3. Results

Our study demonstrates that human digital pads of both tested fingers, the index and the thumb, were adhesive on the whole tested range of surface roughness and at all levels of normal load (Fig. 1). The adhesive forces of the fingertips of the volunteers participating in this study ranged from 2.3 to 167.6 mN (Fig. 1). The strongest adhesion of 14 mN (median) was measured on smooth epoxy resin under a normal load of more than 300 mN. On the rough substrates of 1.3, 10.8, and 55.0 μm grain size, the maximum digital adhesion was considerably lower than that on the smooth surface (Figs. 2 and 3). Analysis of pooled data of the index finger and thumb of all test persons showed that the digital adhesion was significantly different on all four tests surfaces under the different categories of normal load (low normal load = 0–300 mN: Kruskal-Wallis-test, $\chi^2 = 115.182$, $df = 3$, $p = 0.000$; medium normal load = 300–600 mN: Kruskal–Wallis test, $\chi^2 = 68.084$, $df = 3$, $p = 0.000$; high normal load = 600–1000 mN: Kruskal–Wallis test, $\chi^2 = 43.479$, $df = 3$, $p = 0.000$). While no significant difference was found among the three rough surfaces, adhesion on smooth epoxy was significantly higher than that on each of the other three surfaces within the whole range of tested load (0–1000 mN) (Pairwise Wilcoxon signed rank sum test, $P \leq 0.001$) (Fig. 2). On all tested surfaces, we found also significant differences in adhesion among the ten different 100 mN load categories (Kruskal–Wallis test). In pairwise comparisons (Wilcoxon signed rank sum test) pooled data in the load categories lower than 300 mN were in most of the cases significantly different from the 100 mN load categories between 300 and 1000 mN, but also differed from each other (Fig. 3). Hence, the measured adhesive forces of human digital pads were significantly lower at low pressure than at medium and high pressure (> 300 mN) and the adhesion increased with an increasing normal load within the loading regime of 0–300 mN. A positive correlation indicating a dependency of finger pad adhesion on compressive force in humans

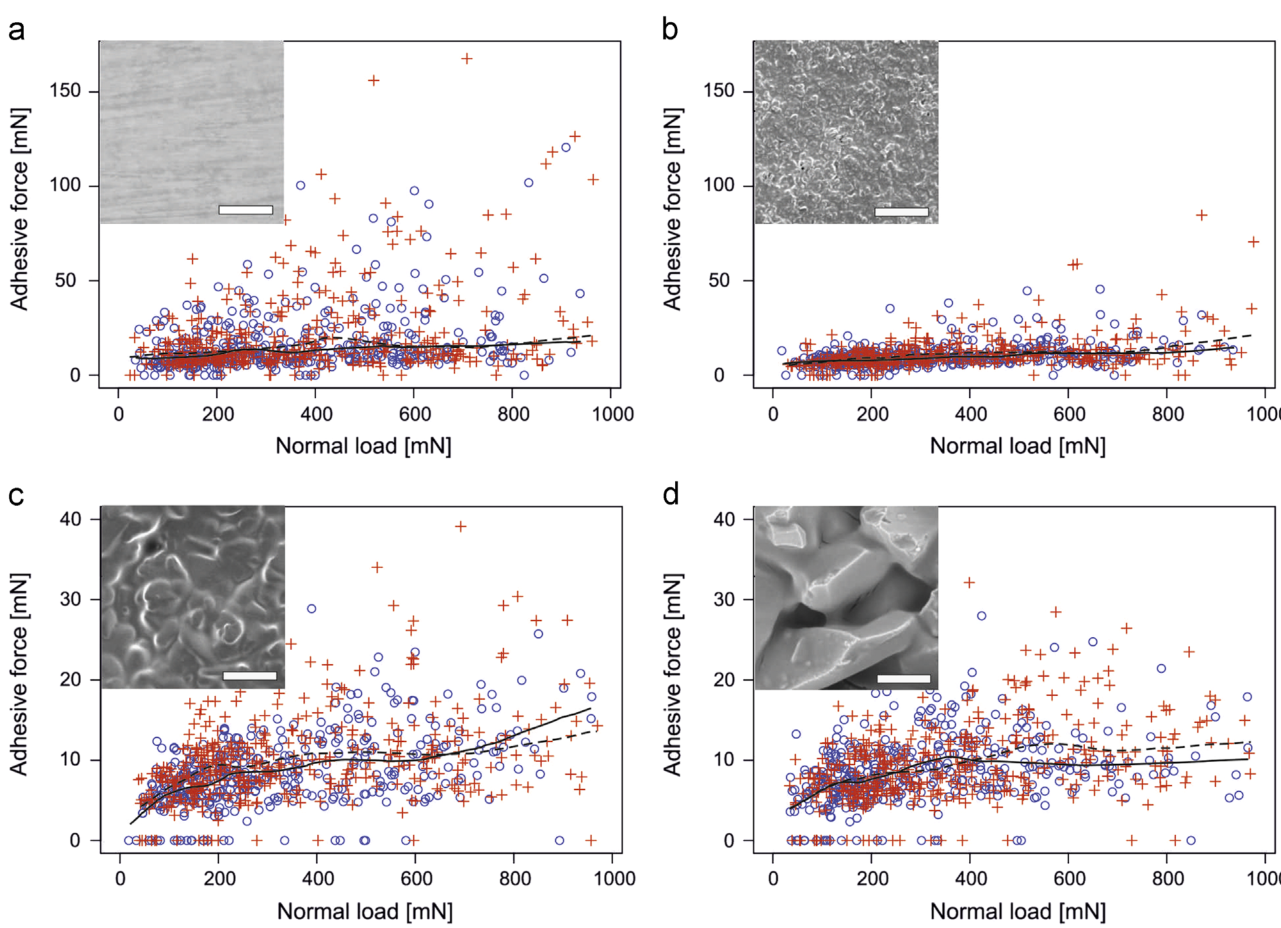

Fig. 1. Adhesive forces of human fingers. The adhesive forces of the tips of index finger (blue circles) and the thumb (red crosses) under different normal load ranging from 0 to 1000 mN measured on epoxy resin replica of a smooth glass surface (a), and surfaces of a grain size of 1.3 μm (b), 10.8 μm (c), and 55.0 μm (d). Scanning electron micrographs of the test surface are presented on the top left side of each graph. The scale bar – 20 μm. The regression lines for measurements of the index finger (black line) and the thumb (dashed line) were calculated by the LOWESS-method.