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Role of occlusion in non-Coulombic slip of the finger pad

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Abstract. Understanding how fingers slip on surfaces is essential for elucidating the mechanisms of haptic perception. This paper describes an investigation of the relationship between occlusion and the non-Coulombic slip of the finger pad, which results in the frictional force being a power law function of the normal load, with an index n; Coulombic slip corresponds to $n = 1$. For smooth impermeable surfaces, occlusion of moisture excreted by the sweat glands may cause up to an order of magnitude increase in the coefficient of friction with a characteristic time of ~ 20 s. This arises because the moisture plasticises the asperities on the finger print ridges resulting in an increase in their compliance and hence an increase in the contact area. Under such steady state sliding conditions a finger pad behaves like a Hertzian contact decorated with the valleys between the finger print ridges, which only act to reduce the true but not the nominal contact area. In the limit, at long occlusion times (~ 50 s), it can be shown that the power law index tends to a value in the range $2/3 \leq n \leq 1$. In contrast, measurements against a rough surface demonstrate that the friction is not affected by occlusion and that a finger pad exhibits Coulombic slip.

Keywords: Finger pad, Friction, Coulombic slip, Occlusion, Skin hydration

1 Introduction

Over a century ago, Katz [1] showed that a finger often oscillates when it slides on most surfaces. These rapid fluctuations are often attributed to irregularities on the surfaces in contact. However, surface irregularities alone are frequently unable to explain the observed fluctuations since they can also arise from simple relaxation oscillations or from more complex phenomena such as, *inter alia*, Schallamach waves. Understanding of the sliding event can assist in explaining the factors that govern the oscillatory mechanisms perceived by the finger through vibrotaction. Such insights would be very valuable since the fluctuations play a determinant role in the perception of textures [2], in motor behaviour [3] and in most instances of haptic behaviour in humans [4]. The fluctuations are a dynamic system response that depends on the tribological properties of the finger pad, and the compliance of the finger in addition to any frictional force measurement device. Evaluating the quasi-static tribological properties in isolation is fundamental to understanding the system dynamics. This is possible when there is continuous sliding, which may occur for some surfaces under particular combinations of normal load and sliding velocity, however the results have proven to be surprisingly complicated. For example, there is evidence that, contrary to classic contact mechanics theory [5], two different coefficients of friction contribute to the net friction. Since they influence the dynamics of contacts, this multiplies the possible stick-slip evolutions of the contact area. In fact, Terekhov and Hayward [6] found that a cutaneous contact evolves differently if the dynamic friction is greater than the static value: the stuck surface area can diminish as the tangential load increases until reaching a *minimal adhesion surface area* where it vanishes abruptly.

The complexity of the tribological properties was also exemplied by the extraordinary experiments of Cartmill [7] who showed that the frictional force, F, of the fingers of small clawless primates such as squirrels depends on a fractional power of the normal load, termed the load index, n, thus $F = kW^n$, where W is the normal load and k is sometimes termed the friction factor. This non-linear frictional behaviour, corresponding to *non-Coulombic slip* ($n < 1$), is also seen for the human finger pad [8] and has been argued to be important in explaining the force modulations arising from tactile interactions with rough surfaces [9]. An intuitive explanation for the occurrence of the decaying harmonics is the distribution and nature of the multiple micro features on the surfaces in contact with the finger [10]. These asperities have arbitrary shapes, and varying sizes and heights, making the signal complex. The sum of the areas of all the contact spots constitutes the real (true) area of contact, A [5]. When two such surfaces (the finger and the counter surface) move relative to each other tangentially under load, the adhesion between the asperities creates the frictional force. This adhesion mechanism relates the frictional force to A by $F = \tau A$ where τ is the interfacial shear strength associated with the rupture of the intermolecular junctions e.g. van der Waals attractive potentials. In the case of organic polymeric materials, such as the *stratum corneum,* τ is a linear function of the mean contact pressure, $p = W/A$, such that $\tau = \tau_0 + \alpha p$ where τ_0 is the intrinsic shear strength and α is a pressure coefficient [11]. The finger pad is topographically rough at the length scales of the finger print ridges and their associated asperities. It is well established that A for any multiple asperity contact is proportional to the normal load, i.e. $A = cW$ where c is a material constant [5]. Thus the adhesion mechanism yields $F = (c\tau_0 + \alpha)W$. Since the terms in brackets are material constants, a multiple asperity contact should be *Coulombic*, i.e. $F = \mu W$ where μ is the coefficient of friction. Thus Cartmill's results [7] would not have been anticipated on the basis of classic contact mechanics given the topographical features of a finger pad.

Actually, the value of μ at a given normal load depends on several variables such as the hydration state of the finger, its displacement, and the sliding time [4]. In particular, skin moisture dramatically affects the contact dynamics during the evolution from sticking to slipping. There is up to an order of magnitude increase in μ during sustained sliding against smooth impermeable surfaces because the asperities on the finger print ridges are plasticised by the occlusion of the excreted moisture from the sweat pores that heavily populate these ridges. This process may be described by first order kinetics with a characteristic time of ~ 20 s [12]. Moreover, excess hydration reduces the tendency of the contact to slip, regardless of the variations of the coefficient of friction [13]. In such cases, different parts of the skin can be in a stick or slip state at the same time.

In the current paper, we investigate the evolution of k and n as a function of the sliding time for smooth and rough surfaces with different hydrophobicities. These parameters are sensitive measures of the prevailing contact mechanics and will thus provide insights about the influence of moisture occlusion. A particular aim is to identify the mechanism that leads to the load dependence of μ. The work involved measurements of the friction as a function of the normal load for a range of occlusion times from first contact until steady state. They were conducted under passive touch conditions at a constant velocity.

2 Experimental

The counter surfaces (75 x 25 mm) were an optically flat glass plate (hydrophilic), a sheet of smooth polypropylene (PP) (hydrophobic), and PP that had been roughened with 240p grade "wet and dry" abrasive paper. The surface textures were evaluated using a profilometer (Sensofar S neox 3D Optical Profiler). The glass and smooth PP had mean Rq values of 2 nm and 50 nm respectively, while that for the rough PP was 6 µm.

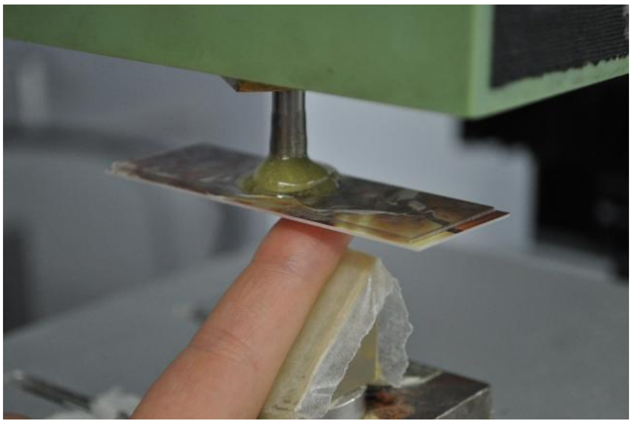

Fig. 1. Photograph of the tribometer configuration used to measure finger pad friction.

The friction measurements were carried out using a Tabor-Eldredge tribometer, which consisted of a balanced beam with a bearing as its fulcrum [12]. The tangential force at one end was measured by two flexible, strain-gauged, cantilever steel beams to which the counter surface was attached via a rigid beam spacer assembly. The left hand index finger of a healthy female volunteer (26 yr) was supported by a sloping platform assembly (Fig.1), which could be raised to bring the finger into contact with the counter surface. The finger was initially washed with soap, rinsed, dried and allowed to equilibrate for a minimum of 10 min. Normal loads in the range 0.02 to 2.0 N were applied by placing weights on the tangential force transducer, directly above the contact region. Motorised actuation allowed a reciprocating motion of ~ 45 mm to be applied at a constant velocity of 24 mm/s for ~ 4 min. Between each load being applied, the finger pad was allowed to equilibrate with the ambient environment (21°C and 55% RH) for about 1 min and the finger pad wiped with a tissue immediately prior to each measurement.

3 Results

In the case of the smooth surfaces, the frictional force increased asymptotically with occlusion time to an approximately steady state value. The values of k and n, as a function of the occlusion time, t, which were obtained from the best fits of data to the power law equation ($F = kW^n$) at specific occlusion times, are shown in Fig. 2 together with the best fits to the following first order kinetics equations:

$$= \ _{\infty} + (n_0 - n_\infty)\exp(-t/\lambda) \quad (1)$$

$$k = k_\infty + (k_0 - k_\infty)\exp(-t/\lambda) \quad (2)$$

where the subscripts 0 and ∞ refer to the time at first contact and at steady state, and λ is a characteristic time. The values of the parameters are given in Table 1 and those for k increase with time and are relatively similar for the two smooth surfaces, which is consistent with the trends in μ obtained previously for a different subject at a single normal load of 0.2 N [12]. The characteristic times are also similar being 24 and 16 s for glass and PP at the same sliding velocity of 24 mm/s compared with 18 and 16 s in the current work. The values of n for both nominally smooth surfaces decrease from about unity to ~ 0.63 and ~ 0.80 for glass and PP.

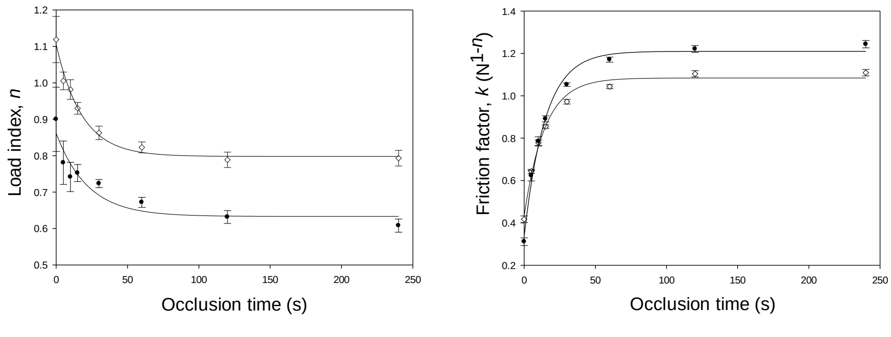

Fig. 2. The parameters n and k as a function of occlusion time for smooth PP (◊) and glass (●). The lines in the left and right hand figures are the best fits to equations (1) and (2) respectively. The error bars represent the standard error of the mean.

Table 1. Parameter values for glass and PP corresponding to equations (1) and (2).

	$_0$	$_\infty$	k_0 (N^{1-n})	k_∞ (N^{1-n})	λ (s)
Glass	0.86±0.03	0.63±0.02	0.34±0.03	1.21±0.02	18±5
PP	1.10±0.01	0.80±0.01	0.43±0.03	1.08±0.02	16±3
Rough PP	0.98±0.01	0.98±0.01	0.53±0.001	0.53±0.001	

The frictional force was relatively independent of the occlusion time for the rough PP; the load index was found to be close to unity (0.98) and the value of k is 0.53 $N^{0.02}$, which is initially greater than that for the smooth surfaces but is less at steady state.

4 Discussion

It might be expected that the load index should be unity at first contact even for the nominally smooth surfaces since the *stratum corneum* will be in a near-glassy state [4] and thus the asperities on the finger print ridges will be relatively non-deformable. Consequently, a multiple asperity contact should be formed with a contribution from the counter surface depending on the extent of the surface roughness. The simplest model of such contacts was proposed by Archard [14] who considered a Hertzian sphere with spherically capped Hertzian asperities on which such asperities of smaller radii were located, and so on. He showed that n tends from 2/3 to unity in the limit. Essentially he demonstrated that the mean asperity contact pressure is constant since the value on existing asperities increases with load but new contacts experience a small pressure. Consequently, τ should be independent of the load.

Asperities reduce the real area of contact and hence the coefficient of friction should decrease with increasing roughness of the counter surface. This is the case here for the values of $\mu\ (= k/W^{1-n})$ at steady state sliding, particularly at small normal loads, but those for glass and smooth PP asymptotically reduce to a similar value at large normal loads that is about a factor of two greater than that for the rough PP. That these values and those of the characteristic times are similar within experimental error suggests that under these sliding conditions the formation of thin water films is not a significant factor, despite the glass being hydrophilic and the PP being hydrophobic. For triangular ridged hard surfaces it has been observed that the friction of the finger pad was relatively independent of the roughness in the range of Rq values studied here [15]. However, the sliding time was not controlled in this work, which is clearly a factor at small loads for the nominally smooth surfaces. The lack of sensitivity to the sliding time observed in the current study for rough PP suggests that for rough surfaces there is sufficient interstitial voidage between the asperity valleys for moisture to diffuse readily and thus eliminate the effects of occlusion. Alternatively, the plasticisation of the asperities on the finger print ridges and resulting increase in compliance is not sufficient to change significantly the extent to which they conform to those on the PP.

To understand the origin of n being less than unity for smooth surfaces at steady state occlusion, it is necessary to assume that the loading of the finger pad is Hertzian [5] at the length scale of the gross curvature. This is consistent with the measured parabolic pressure profile [16] and the variation of A with load [8] for the range of normal loads invesitigated here. Hertzian contact assumes linear elastic deformation and it arguable that more complex material models, e.g. viscoelastic or hyperelastic [17], would be more appropriate but Hertzian contact provides a useful first order interpretation of the data. The frictional force for such a contact, assuming that the adhesion mechanism applies, is given by the following expression [18]:

$$F = \pi\tau_0[3R(1-\nu^2)/4E]^{2/3}W^{2/3} + \alpha W \quad (3)$$

where E, R and ν are the Young's modulus, mean radius and Poisson's ratio of the finger pad. It may be approximated by a power law in W such that the load index is in the range $2/3 \geq n \geq 1$ depending on the relative values of the load coefficients in equation (3) [18]. Thus, for example, in the case of an elastomeric Hertzian contact, $\alpha = 0$ and thus $n = 2/3$ [11], which was the case considered by Archard [14]. The values of n observed here are consistent with the gross contact area of individual finger print ridges being independent of load due to the much greater gross compliance of the finger pad. Given the approximately trapezoidal cross-section of the finger print ridges, a reasonable model of the finger pad is a smooth Hertzian spherical cap with triangular valleys between the finger print ridges. Thus the friction may be described by equation (3) after accounting for the ratio of the real and nominal areas of contact, ξ:

$$F = \pi\xi\tau_0[3R(1-\nu^2)/4E]^{2/3}W^{2/3} + \alpha W \quad (4)$$

That the value of n_∞ is slightly less than 0.67 for the glass and the initial value for PP is greater than unity reflects either the approximate nature of the model or experimental uncertainties. The complexity of the finger pad contact, such as a tendency to roll during the application of the tangential force, is likely to be a contributory factor. However, it has been observed that the contact area decreases under the action of a tangential load before any slip is initiated [13]. Thus if the rate of increase of the residual area with normal load was less than expected from the Hertz equation then a value of $n < 2/3$ is theoretically possible. In terms of the Archard model, as the extent of occlusion increases from first contact, the smallest asperities will be preferentially flattened because of their greater contact pressure and thus the value of n will decrease. The steady state occlusion time is surprisingly long (~50 s) and will reflect the physiological factors involved and the possibility of some moisture being lost due to deposition on the counter surface or interface diffusional loss through the contact.

The steady state values of n increase with the roughness of the surfaces studied. For glass, the initial value is < 1, which suggests that the moisture content of the unoccluded *stratum corneum* is sufficient to cause significant deformation of the asperities on the finger print ridges. However, the initial value for smooth, like the rough PP is ~ 1, which shows that the asperities on even relatively smooth surfaces have a considerable influence on unoccluded *stratum corneum*. This is consistent with the steady state value of > 2/3, which indicates that even fully occluded *stratum corneum* is extremely sensitive to small topographical features. The important point is that this load index is greater than that for glass rather than being > 2/3, since it is theoretically possible for a smooth Hertzian contact to exhibit a value > 2/3 depending on the relative values of the coefficients in equation (4) as mentioned previously.

5 Conclusion

In the current work, the quasi-static component of the kinetic friction as a function of the occlusion time has been monitored. The friction factor and load index are instrumental in defining the relationship between the friction coefficient and the load exerted by the finger. For smooth surfaces, the occlusion time dependent load index provides a sensitive measure of the transition from a multiple asperity Coulombic contact to one that is non-Coulombic due to the finger print ridges developing an intimate contact with the counter surface. Rough surfaces appear to be indifferent to occlusion as evidenced by the insensitivity of the coefficient of friction to the sliding time. The results represent an important precursor to understanding the much more complex dynamic behavior elicited by the finger pad in haptic contacts such as vibrotaction. Moreover, it should provide a basis for elucidating the complex evolution of a finger pad contact when tangentially loaded. For example, whether or not the initial reduction of the contact area is due to a peeling mechanism prior to true slip. This phenomenon may play an important role in our ability to detect slip, which is crucial in grip function. Finally, the current work was limited to one subject and three surfaces but a recent larger study has concluded that occlusion has a major effect on the variability in μ for different subjects [19].

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7 References

1. Krueger, L.E.: Tactual Perception in Historical Perspective: David Katz's World of Touch. Tactual Perception; A Sourcebook 1–55, Cambridge University Press (1982)
2. Bensmaia, S.J., Hollins, M., Washburn, S.: Vibrotactile Adaptation Impairs Discrimination of Fine, but not Coarse Textures. Somatosensory Motor Res. 18, 253–262 (2001)

3. Wiertlewski, M., Endo, S., Wing, A.M., Hayward, V.: Slip-Induced Vibration Influences the Grip Reflex: A Pilot Study. Proceedings of the 2013 World Haptics Conference, 627–632 (2013)
4. Adams, M.J., Johnson, S.A., Lefèvre, P., Lévesque, V., Hayward, V., André, T., Thonnard, J.L.: Finger Pad Friction and its Role in Grip and Touch. J. R. Soc. Interf. 10, 20120467 (2013)
5. Johnson, K.L.: Contact Mechanics, Cambridge University Press (1987)
6. Terekhov, A., Hayward, V.: Minimal Adhesion Surface area in Tangentially Loaded Digital Contacts. J. Biomech. 44, 2508–2510 (2011)
7. Cartmill, M.: The Volar Skin of Primates: Its Frictional Characteristics and Their Functional Significance. Am. J. Phys. Anthrop. 50, 497–509 (1979)
8. Warman, P.H., Ennos, A.R.: Fingerprints are Unlikely to Increase the Friction of Primate Fingerpads. J. Exp. Biol. 212, 2016–2022 (2009)
9. Wandersman, E., Candelier, R., Debrégeas, G., Prevost, A.: Texture-induced Modulations of Friction Force: The Fingerprint Effect. Phys. Rev. Lett. 107, 164301 (2011)
10. Wiertlewski, M., Hudin, C., Hayward, V.: On the 1/f Noise and Non-Integer Harmonic Decay of the Interaction of a Finger Sliding on Flat and Sinusoidal Surfaces. Proceedings of the 2011 World Haptics Conference, 25–30 (2011)
11. Briscoe, B.J., Arvanitaki, A., Adams, M.J., Johnson, S.A.: The Friction and Adhesion of Elastomers. Trib. Ser. 9, 661–672 (2001)
12. Pasumarty, S.M., Johnson, S.A., Watson, S.A., Adams, M.J.: Friction of the Human Finger Pad: Influence of Moisture, Occlusion and Velocity. Trib. Lett. 44, 117–137 (2011)
13. Andre, T., Levesque, V., Hayward, V., Lefevre, P., Thonnard, J.L.: Effect of Skin Hydration on the Dynamics of Fingertip Gripping Contact. J. R. Soc. Interf. 6, 1574–1583 (2011)
14. Archard, J.F.: Elastic Deformation and the Laws of Friction. Proc. R. Soc. Lond. A, Math. Phys. Sci. 243, 190–205 (1957)
15. Tomlinson, S.E., Carré, M.J., Lewis, R., Franklin, S.E.: Human Finger Contact with Small, Triangular Ridged Surfaces. Wear 271, 2346–2353 (2011)
16. Pawluk, D.T., Howe, R.D.: Dynamic Contact of the Human Fingerpad Against a Flat Surface. ASME J. Biomech. Eng. 121, 605–610 (1999)
17. Lin, D.C., Shreiber, D.I., Dimitriadis, E.K., Horkay, F.: Spherical Indentation of Soft Matter Beyond the Hertzian Regime: Numerical and Experimental Validation of Hyperelastic Models. Biomech. Model. Mechanobiol. 8, 345–358 (2009)
18. Adams, M.J., McKeown, R., Whall, A.: A Micromechanical Model of the Confined Uniaxial Compression of an Assembly of Elastically Deforming Spherical Particles. J. Phys. D: Appl. Phys. 30, 912–920 (1997)
19. Derler, S., Rossi, R.M., Rotaru, G.M.: Understanding the Variation of Friction Coefficients of Human Skin as a Function of Skin Hydration and Interfacial Water Films. Proc. Inst. Mech. Eng. Pt. J: J. Eng. Trib., in press (2014)