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RESEARCH ARTICLE

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Role of friction and tangential force variation in the subjective scaling of tactile roughness

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Abstract The present study examined the contribution of normal (Fz) and tangential (Fx) forces, and their ratio, kinetic friction (Fx/Fz), to the subjective magnitude estimations of roughness. The results suggested that the rate of variation in tangential stroking force is a significant determinant of roughness perception. In the first experiment, six volunteer subjects scaled the roughness of eight surfaces explored with a single, active scan of the middle finger. The surfaces were 7.5×2.4-cm polymer strips embossed with truncated cones 1.8 mm high with a spatial period of 2.0 mm in the transverse direction and 1.5–8.5 mm in the longitudinal, scanning direction. The surfaces were mounted on a six-axis force and torque sensor that measured the perpendicular, contact force (normal to the skin surface) and the tangential force along the axis of stroking. The results confirmed the findings of an earlier study that magnitude estimates of perceived roughness increase approximately linearly up to a longitudinal spatial period of 8.5 mm. Across subjects, no consistent correlations were found between perceived roughness and either the mean normal or tangential force alone. Although significant positive correlations were found between roughness and mean kinetic friction for all subjects, they were not as consistently robust as one might have expected. Furthermore, instantaneous kinetic friction varied widely over the course of a single stroke because of within trial oscillations in the tangential force. The amplitude of these oscillations increased with the longitudinal spatial period and their frequency was determined by a combination of the spatial period and the stroking velocity. These oscillations were even more conspicuous in the first derivative or rate of change of the tangential force (dFx/d*t*), which was quantified as the root mean square (RMS) of the tangential force rate. The mean normalized RMS proved to be strongly correlated with subjective roughness, averaging 0.88 for all subjects. In order to dissociate the fluctuations in tangential force from both the surface structure and the mean kinetic friction, a second experiment was performed on six additional subjects who estimated the roughness of identical lubricated and unlubricated (dry) surfaces. Lubrication with liquid soap reduced the mean kinetic friction by approximately 40%, the RMS of the tangential force rate by slightly more than 21% and the subjective estimates of roughness by 16.4%. Taken together, the results suggest that in tactile exploration, the RMS of the tangential force rate may be an important determinant of subjective roughness.

Keywords Roughness estimation · Kinetic friction · Rate of change in tangential force · Texture · Active touch

Introduction

There has been a long-standing and continuous discussion in somatosensory psychophysics about what physical features of surface topography or texture contribute to the subjective perception of roughness. Roughness, however, is the mental product of an integrative perceptual process, whereas texture refers to the topographical irregularities measured in units of horizontal and vertical distance between the peaks and valleys (or ridges and grooves) measured with a profilometer.

A wide variety of stimulus features have been shown to affect the subjective sensation of roughness. The size and spacing of the tactile elements have been shown to play a crucial role. Using simple manufactured patterns where the tactile elements are independently varied in size and spacing, it has been shown that roughness increases as the distance between raised elements (ridges or raised dots) is increased (Lederman and Taylor 1972; Taylor and Lederman 1975; Sathian et al. 1989; Connor

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et al. 1990; Connor and Johnson 1992; Meftah et al. 2000). In contrast, increases in the size of the raised elements (e.g., ridge width) produce a modest decrease in roughness. Finally, an increase in the height of the raised elements also increases roughness (Blake et al. 1997). Together, these observations suggest that a critical factor in roughness appreciation may be the depth to which the finger penetrates into the groove. Consistent with this, Lederman and Taylor (1972) reported that increasing the contact force normal to the skin surface significantly increased the subjective sensation of roughness. From this observation it would appear that the cross-sectional area of the finger within the groove and the deviation of the skin from its resting position are important factors contributing to the sensation of roughness.

Given the importance of contact force described above and the importance of tangential movement to roughness appreciation demonstrated by Morley et al. (1983), one might suppose that friction, or the ratio of the tangential to normal force required to initiate sliding of a finger applying a given contact force normal to the supporting surface (Bowden and Tabor 1982), might be an important parameter. Surprisingly, however, Taylor and Lederman (1975) reported that surface lubrication, which significantly reduced the mean static coefficient of friction, had no effect on roughness estimates. They concluded that, compared with groove width, mean static friction has little or no impact on roughness magnitude estimation. The latter study had, however, several weaknesses. First, the range of spacings tested (0.63–1.25 mm) was very narrow. This contrasts with recent results that have shown that roughness shows a near linear increase over spatial periods ranging from 1.5 to 8.5 mm (rectangular arrays of raised dots; Meftah et al. 2000). Consequently, the range of element spacings tested may have been too small for friction to have contributed significantly to the results. Second, friction was not measured during the experimental scans. Instead, friction was estimated using a static measure, and this along, rather than across, the crests of the ridges. Since the subjects scanned their digits across the ridges in the experiments, it is not clear what the actual change in friction might have been under their experimental conditions.

It therefore seemed worthwhile to reinvestigate the potential contribution of friction to the sensation of roughness. To examine this issue we used a sensitive three-dimensional force sensor to measure the instantaneous changes in tangential and normal forces applied by the hand when subjects were asked to evaluate surface roughness. The results show that roughness estimates decrease when kinetic friction is reduced. However, the most important variable appeared to be fluctuations in tangential force, which correlated well with the subjective sensations of roughness and with the physical dimensions of the textured surfaces.

Materials and methods

Surfaces

Eight flexible polymer surfaces (7.5×2.4 cm) identical to those employed by Meftah et al. (2000) were used for roughness estimation in this experiment. The surfaces were embossed with a rectangular array of truncated cones, 0.6 mm in diameter and 1.8 mm in height as shown in Fig. 1. The spatial period, or the center-to-center distance between adjacent cones, was 2.0 mm in the transverse direction and varied from 1.5 mm to 8.5 mm in the longitudinal or scanning direction.

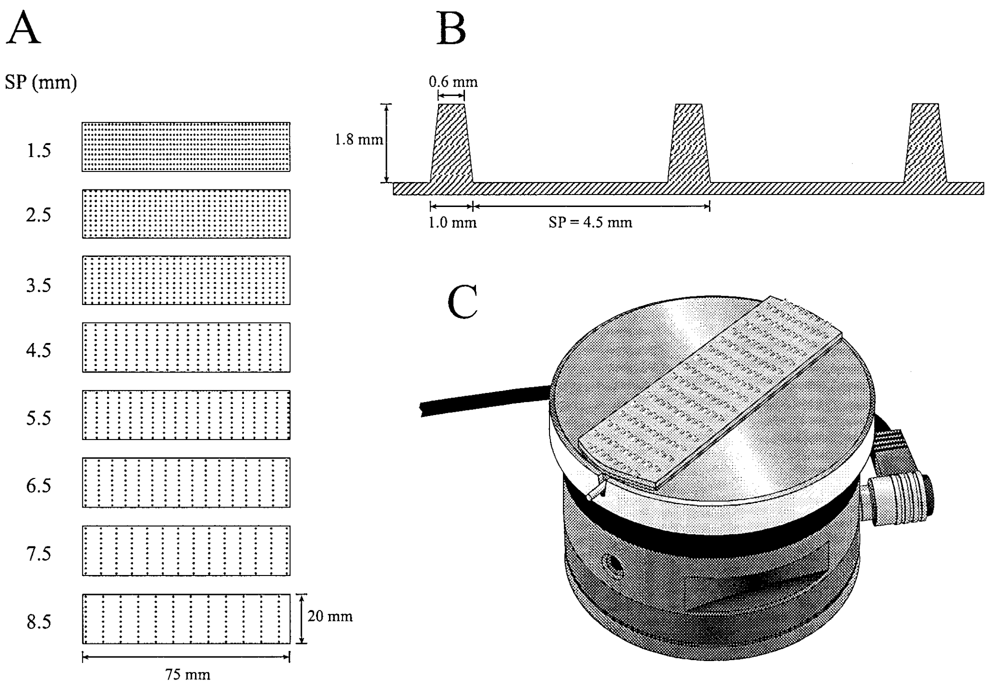


Fig. 1 **A** Overhead view of the spacing of the truncated cones. **B** Side view of one surface (4.5 mm spatial period, *SP*). **C** shows the 4.5-mm surface in the receptacle mounted on the force sensor

Force measurement

To measure the forces employed during the tactile exploration, each surface was glued to a rigid aluminum disk that fit snugly into a receptacle mounted on an ATI Gamma six-axis force and torque transducer (shown in Fig. 1C). The test surfaces had the same length as the diameter of the force and torque sensor. On each trial a new surface and disk was inserted into the receptacle. Small slots cut into the sides of the receptacle shown in Fig. 1C ensured that all surfaces were aligned identically along the *x*-axis of the force sensor. The force sensor produced analog voltages corresponding to three axes of linear force (Fx, Fy, Fz), which were fed to a proprietary analog to digital converter with 16-bit precision at a conversion rate of 250 Hz, allowing the three torsional forces to be calculated as well.

Subjects and tactile exploration task

Six, naive subjects (four women and two men, ages 20–30 years) volunteered to participate in experiment 1. A further six subjects (four women and two men, ages 19–34 years) participated in experiment 2. The ethics committee of the Faculty of Medicine of the Université de Montréal sanctioned the study and all subjects gave their informed consent before participating in the experiment.

The subjects were comfortably seated at a table facing the experimenter and were requested to position the distal phalanx of the middle finger just above but not touching the test surface mounted on the 3D force and torque sensor. An enclosed box shielded the transducer and the various test surfaces from the subjects' view. At the beginning of the session, the subject was informed that the task would be to rate the roughness of a series of surfaces using a whole number scale of the subject's own choosing. When the middle finger was correctly positioned above the force transducer, the subject was given a signal to lower the finger until it made contact with the test surface. Upon contact with the test surface, the subjects were asked to slide the finger along the 7.5-cm length of the test surface in the same direction as the variations in spatial period. The subjects were instructed to use a single continuous distal-to-proximal scan and then to attribute a whole-number score to the perceived roughness magnitude. Eight test surfaces were presented 6 times in a pre-established pseudorandom order for a total of 48 presentations in experiment 1. In experiment 2, the total number of trials was doubled: on half the trials the surfaces were lubricated with liquid soap, and on the other half the surfaces were dry (unlubricated). The two conditions (lubricated and unlubricated) were interleaved in pseudorandom order during the experiment. The subjects rinsed and dried the finger after each trial. Although Lederman (1979) has shown that subjects are capable of judging tactile roughness on the basis of sounds alone, the relatively soft polymer surfaces, the high ambient noise level and the enclosure of the hand and sensor within a box seemed adequate to prevent this use of auditory cues. Moreover, the subjective estimates in the present study were similar to those of a previous study by Meftah et al. (2000) in which auditory cues had been expressly excluded.

Before data collection began, the subjects were given three practice trials. Although the subjects were not informed, the three surfaces presented on the practice trials represented the upper, lower and middle spatial periods. The subjects were free to choose the force and the stroking speed that was judged most appropriate. The subjects determined their own rating scale to reflect their roughness magnitude ratings. No attempt was made to assist the subject at arriving at a definition of roughness. However, at the conclusion of data collection each subject was asked how roughness might be defined and how many different stimuli were used in the experiment.

Data acquisition and analysis

Computer collection and storage of data was automatically triggered when the finger contacted the 3D force and torque sensor with a perpendicular or contact force greater than 0.2 N. For each trial, the normal force (Fz) and the tangential force (Fx) in the stroking direction were recorded until the finger broke contact with the test surface. The mean kinetic friction was calculated as the ratio of the average Fx to average Fz for each trial. The six-axis force measurements allowed the instantaneous position of the finger to be computed, and when combined with the total trial duration, the mean stroking velocity could be calculated on every trial. At the completion of each trial, the experimenter noted the numerical roughness estimate given by the subject. If the experimenter judged the force data to contain artifacts of any kind, the trial was rejected and that trial was then repeated at the end of the sequence. In order to facilitate the statistical comparisons between subjects, roughness estimates were normalized by dividing the estimate on each trial by the numerical average of all the estimates in the experiment (48 or 96).

Results

Experiment 1

Roughness estimates and spatial period

This study was predicated on the assumption that a correlation exists between a subject's roughness magnitude estimation and the spatial period of the stimulus. Therefore, an important first step was to replicate the earlier results of Meftah et al. (2000). Figure 2 shows the strong linear correlations between the normalized roughness estimates and spatial period. The correlations, which ranged from r=0.86 to r=0.96, were all statistically significant (P<0.01), indicating a close relationship between subjective roughness and spatial period. The results confirmed the findings of Meftah et al. (2000), and extended these to include active as well as passive touch.

In these experiments, subjects were free to choose their own exploratory strategy. Consequently stroking speed varied considerably between subjects from a minimum of 10 mm/s for subject 6 to a maximum of

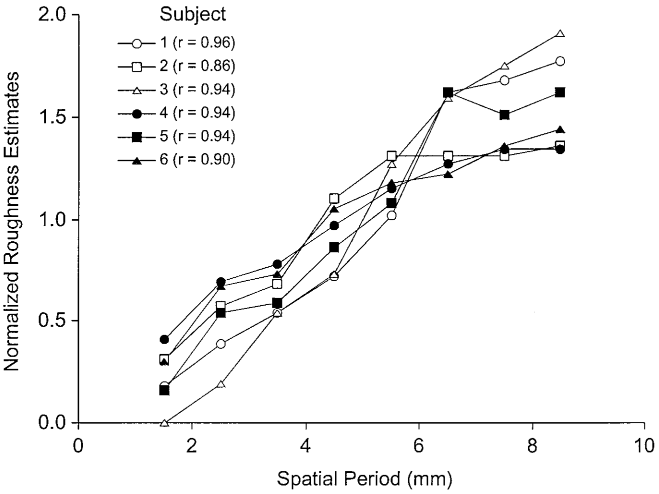


Fig. 2 Mean normalized roughness estimates in six subjects for surfaces with spatial periods ranging from 1.5 to 8.5 mm (experiment 1)

Table 1 Correlations, *r*, between roughness estimates or spatial period and average force (tangential, Fx, and normal, Fz) measured in each trial of experiment 1 (*n*=48)

Subject	Normalized estimates		Spatial period	
	Tangential *F*	Normal *F*	Tangential *F*	Normal *F*
1	0.78*	0.07	0.79*	0.06
2	0.18	–0.05	0.19	–0.03
3	–0.32	–0.52*	–0.41*	–0.62*
4	0.47*	–0.63*	0.43*	–0.67*
5	0.51*	–0.41	0.59*	–0.38*
6	0.30	–0.51*	0.27	–0.51*

*P<0.01

157 mm/s for subject 5. Inspection of Fig. 2 shows that despite these differences in stroking speed, the psychophysical curves were similar across subjects.

When interviewed at the conclusion of testing, the majority of the six subjects reported thinking that they had scaled only three to four different surfaces, although one subject did report scaling as many as seven different surfaces. In general, most subjects indicated that they were aware that the spacing between the rows of asperities increased, and that this distance increased the sense of roughness. Overall, the subjects felt that three classes of stimuli were used in the study – least rough, intermediate and very rough – and that the intermediate spatial periods were the most difficult to distinguish.

Normal and tangential forces exerted by the finger during stroking

In order to determine the contribution of variations in the tangential and normal forces to the results, linear regression analysis was applied to the results of each subject. Table 1 A presents the correlations between the roughness estimates and the average normal and tangential forces for all six subjects. Although several of the tangential force correlations were significantly positive and several of the normal force correlations were significantly negative, there were many non-significant correlations as well. Overall roughness did not show a systematic relationship with either the normal or the tangential force alone. Given the inconsistency of these relationships for all subjects, it was difficult to imagine that the average individual forces by themselves were a determining factor in the roughness estimates. Table 1 B presents similar widely varying correlations between the spatial periods and the normal and tangential forces, again suggesting that there was no invariant relationship.

Roughness, spatial period and the mean kinetic friction

For each trial, in each subject, the mean kinetic friction was calculated from the average tangential and normal forces (Fx/Fz). Although the correlations between roughness estimates and mean friction were statistically significant for all subjects (see Table 2), they averaged only 0.64 for three of the six subjects, which was not particularly robust. A second series of correlations were calculated between mean kinetic friction and spatial period, and are plotted in Fig. 3. For comparison the roughness estimates are also shown on the same figure. Again although the correlations between mean friction and spatial period were all statistically significant (P<0.01), they ranged between 0.65 and 0.88. The slope of the relationship varied widely between subjects, and as Fig. 3 indicates, the mean friction varied substantially between subjects for the same surface. Moreover, considerable variations in friction occurred within the same subject for the same spatial period (see bars showing the range in Fig. 3).

Table 2 Correlations, *r*, between roughness estimates and mean kinetic friction, Fx/Fz, in experiment 1 (*n*=48)

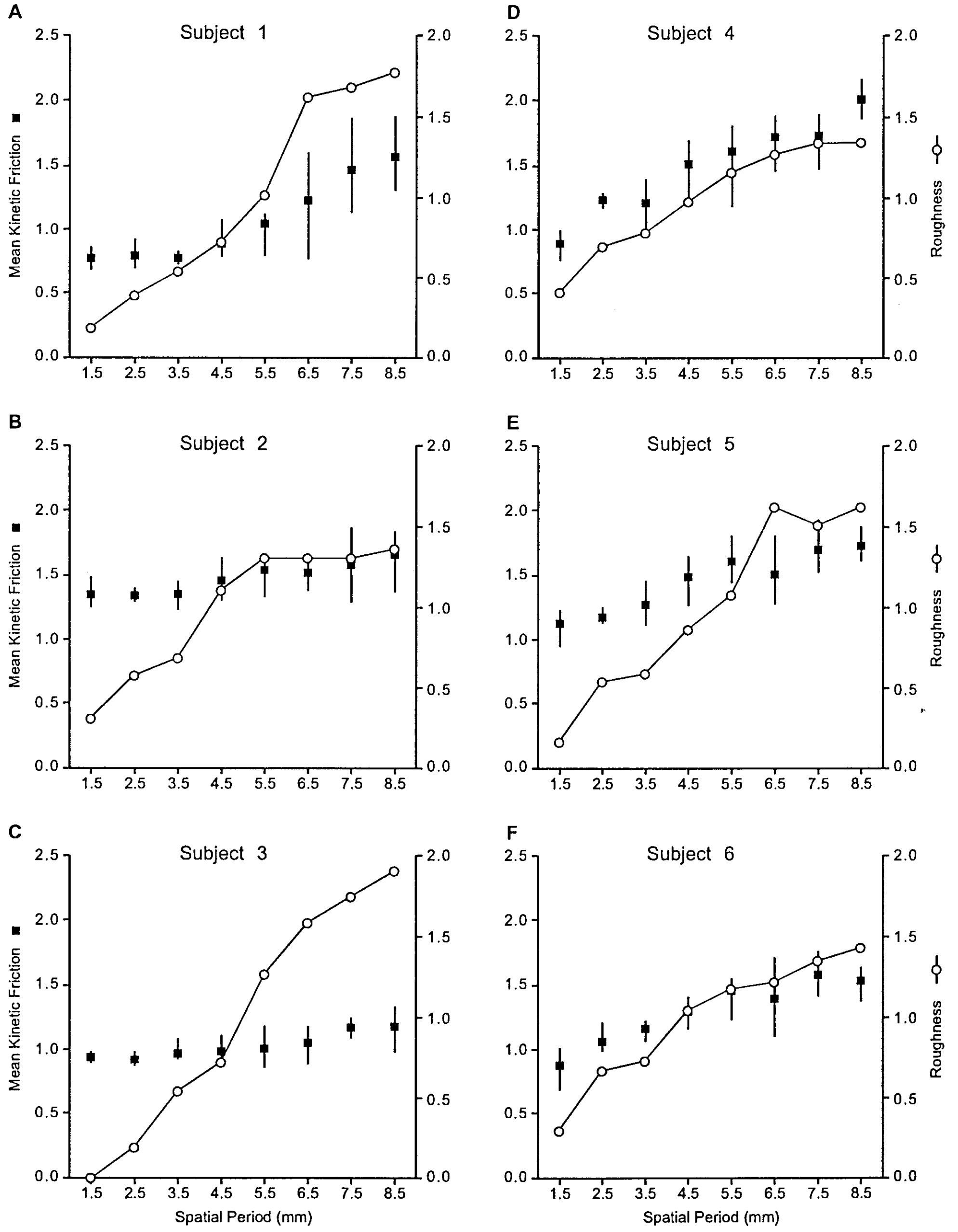
Subject	Correlation
1	0.78*
2	0.65*
3	0.64*
4	0.63*
5	0.88*
6	0.85*

*P<0.01

Rate of change in tangential force

Although significant positive correlations were found between subjective roughness and the mean friction, the individual traces shown in Fig. 4 indicate that averaging the ratio of tangential to normal forces obscured one of the most salient features of the textured surfaces. That is, it failed to take into account the high-amplitude tangential force oscillations characteristic of the surfaces with greater spatial periods. The normal and tangential force traces during a single representative trial for each spatial period for a single subject (subject 1) are shown in Fig. 4. These examples show that the normal (lower trace) force and tangential force (upper trace) increased approximately in parallel until a relatively stable plateau and constant stroking speed were achieved. The most striking feature of Fig. 4 is the relative similarity of the normal forces for all the spatial periods compared to the marked alterations in the form of the tangential force. For the lower spatial periods, the tangential force displays only a few high-frequency, small-amplitude oscillations. However, the cyclic fluctuations became more pronounced above the 5.5-mm spatial period where the oscillations were of lower frequency and greater amplitude. The stroking velocity no doubt determined the oscillatory frequency, whereas the amplitude variations were determined by the stick-slip sequences incurred as the rows of cones successively passed over the fingertip skin. The number of cycles was determined by the number of rows of cones encountered by the fingertip regardless of the stroking velocity.

Fig. 3A–F The mean and range of kinetic friction (Fx/Fz) is plotted against the spatial period for each of the six subjects (ordinate *on the left*) who participated in experiment 1. The normalized roughness estimates for the same subjects are also plotted (*right-hand ordinate*)

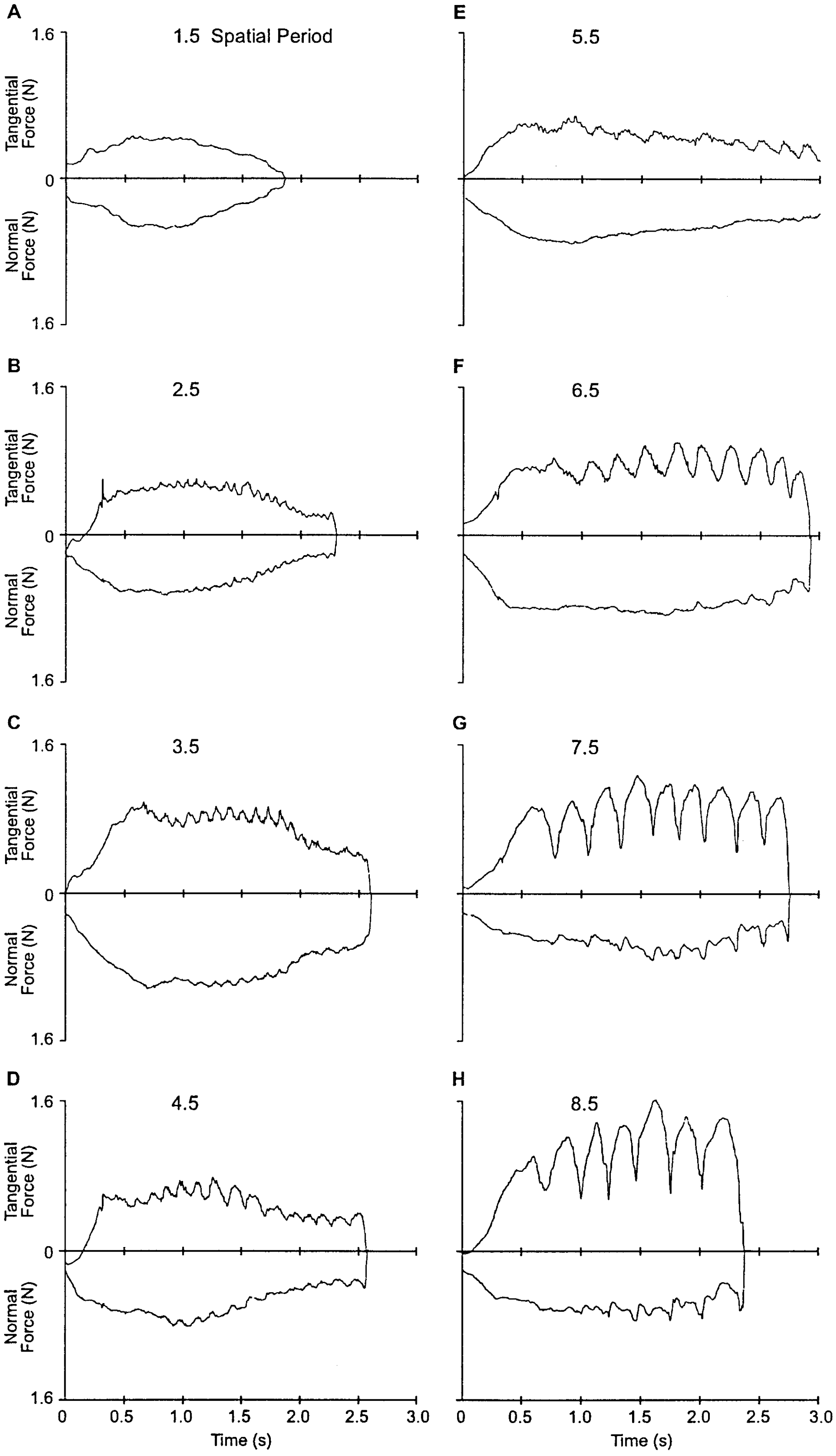


Instantaneous kinetic friction

Since there were also trial-by-trial variations in the normal force as well as the tangential force, it was decided to examine the instantaneous kinetic friction computed as the ratio of the tangential to normal force measured every 4 ms in each trial. Figure 5 illustrates the instantaneous kinetic friction computed for each of the trials illustrated in Fig. 4. The instantaneous kinetic friction showed increasing fluctuations in amplitude with increasing spatial period. However, the instantaneous kinetic friction did not appear to reveal any additional information that was not present in the oscillations in the tangential force.

For this reason the variation in the tangential force was thought to be the major parameter contributing to the roughness sensation associated with the greater spatial periods. It seemed reasonable to suppose that dynamically sensitive skin mechanoreceptors might respond to the first time-derivative or rate of tangential force variation (dFx/d*t*). The 1.5-mm spatial period produced very low-amplitude, high-frequency fluctuations in the tangential force, whereas the 8.5-mm spatial period produced high-amplitude, low-frequency oscillations. To quantify and illustrate this observation, we proceeded to calculate and plot the rate of tangential force variation for each trial. Examples of the tangential force dFx/d*t* for single trials with the surfaces with shortest and longest

Fig. 4A–H The tangential (Fx, *upper traces*) and normal (Fz, *lower traces*) forces present in an individual trial for spatial periods from 1.5 to 8.5 mm in subject 1 (experiment 1)



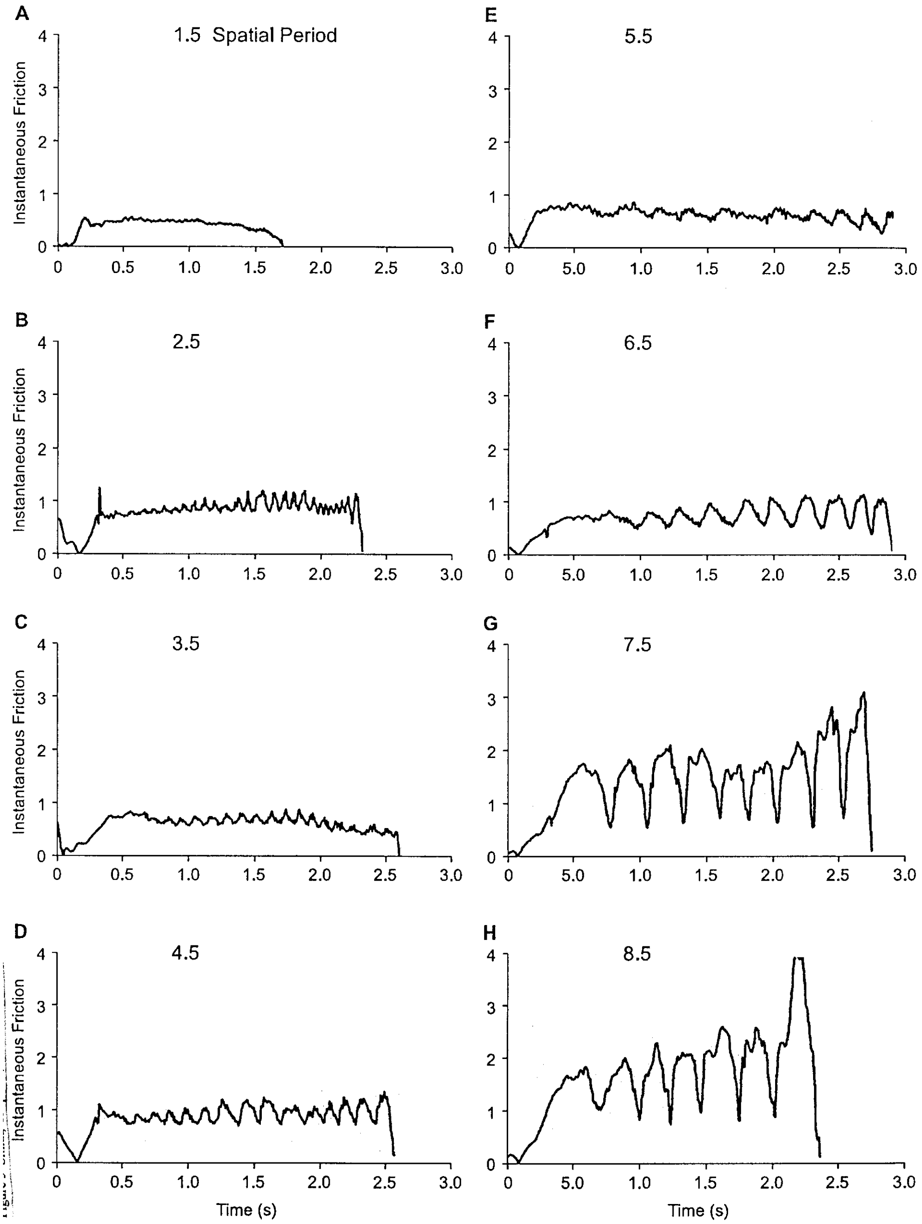


Fig. 5A–H Instantaneous kinetic friction (Fx/Fz) calculated from the trials illustrated in Fig. 4

spatial periods for each of the six subjects are shown in Fig. 6. The tangential force for the smallest spatial period was characterized by only small fluctuations in the force rate whereas the longest spatial period was associated with high-amplitude fluctuations in all subjects. Although the amplitude and stroking speed varied from subject to subject, there was a marked and consistent difference in the tangential force variation between the shortest and the longest spatial period for all subjects.

The peak-to-peak fluctuations in the dFx/d*t* of the tangential force can be quantified by calculating the root mean square (RMS) of the derivative. In order to eliminate the transients associated with the finger contacting and breaking contact with the force sensor, we routinely removed the first and last 100 ms from the derivative traces. However, all the traces were inspected and the start and stop limits were adjusted to eliminate unwanted initial or terminal transients before calculating the RMS. In general, the RMS proved to be a reliable measure of the average amplitude of the fluctuations in the dFx/d*t*. For instance in Fig. 6, the RMS value is indicated beside each of the derivative force traces. Although the absolute RMS values fluctuated considerably from subject to subject, the RMS associated with the smallest spatial period was consistently smaller than the RMS measured with largest spatial period. Moreover, the correlation between the mean subjective roughness estimates and the mean tangential force rate RMS (shown in Table 3) ranged from 0.80 to 0.95, which was higher than the correlations with mean friction. These results indicate that the RMS may be an important parameter of the subjective sensation of roughness.

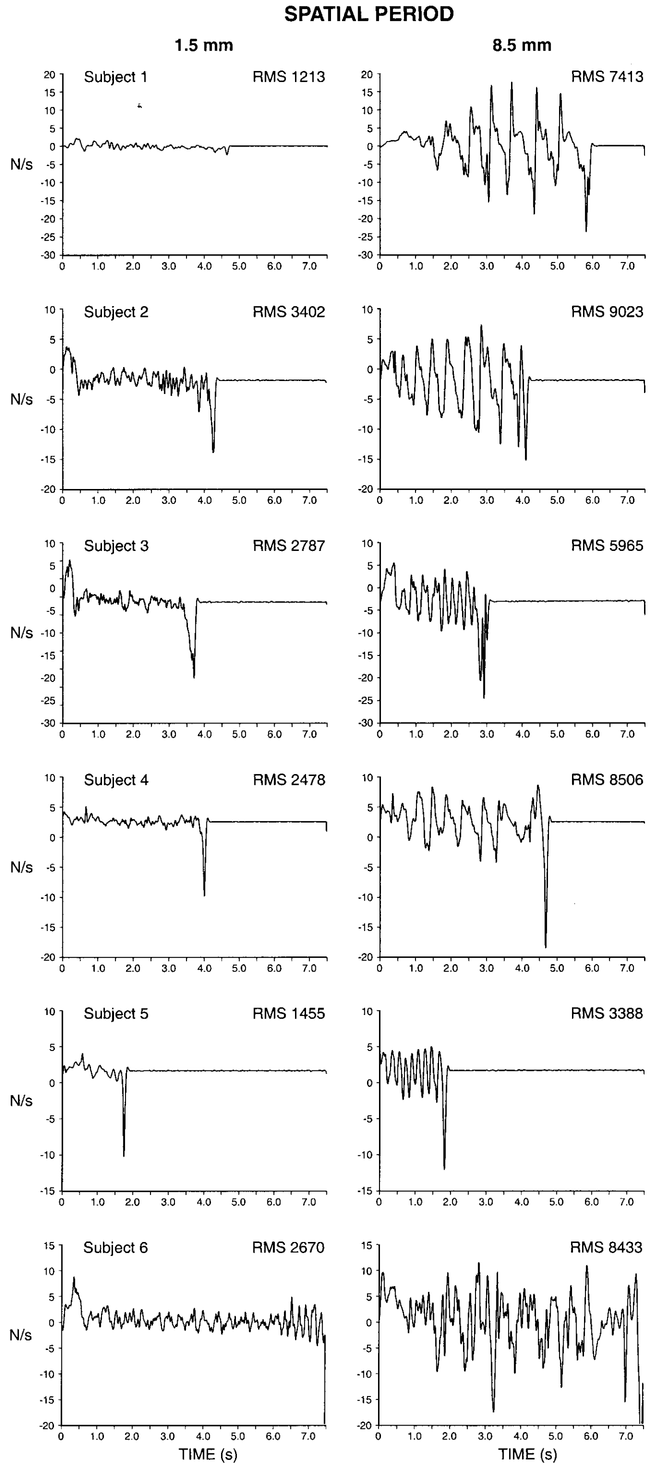


Fig. 6 Examples of the first time derivatives of the tangential force (dFx/d*t*) for each of the six subjects in experiment 1 as they scanned either the 1.5-mm spatial period surface (*left*) or the 8.5-mm surface (*right*)

Table 3 Correlations, *r*, between roughness estimates and mean RMS of variations in tangential force, dFx/d*t*, in experiment 1 (*n*=48)

Subject	Correlation
1	0.95*
2	0.80*
3	0.93*
4	0.92*
5	0.83*
6	0.85*

*$P<0.01$

Experiment 2

Experiment 1 demonstrated that roughness estimates were correlated with spatial period, kinetic friction and variation in tangential force. Therefore, a second experiment was needed to address a set of three interrelated questions raised by the first experiment. First, could kinetic friction be dissociated from the surface structure by lubrication? By applying a lubricant coating it should be possible to produce two different coefficients of kinetic friction for the same surface features. Second, would lubricating the surfaces also reduce the RMS of the tangential force? And, finally, would lubricating the surfaces reduce the subjective estimates of roughness?

Since lubricated and unlubricated (dry) surfaces were presented randomly, the subjects were instructed to rinse and dry the probing finger between each trial. The data were subjected to three separate, two-way analyses of variance (2 coating conditions by 8 spatial periods) using Systat, V9.1 software for the following dependent variables: surface kinetic friction, mean normalized tangential force rate RMS, and normalized roughness estimates. The RMS values for each subject, on each trial, were normalized by dividing them by the mean RMS for all lubricated and unlubricated trials for a given subject.

Adding liquid soap to the surfaces significantly reduced the mean kinetic friction from 0.81 to 0.48 ($F_{(1,80)}=32.440$, $P<0.001$), which is a reduction of approximately 40%. The spatial period was also a significant main effect ($F_{(7,80)}=2.557$, $P=0.02$), but the lubricant by spatial period interaction was not ($P=0.82$). It appears from these data that the lubricant successfully dissociated the kinetic friction from the surface structure as reflected by the spatial period.

The lubrication also significantly reduced the tangential force rate RMS for all subjects. Soaping the surfaces decreased the mean normalized tangential RMS by an average of slightly more than 21% ($F_{(1,80)}=17.42$, $P<0.001$). The spatial period was also a significant main effect ($F_{(7,80)}=32.76$, $P<0.001$), but the lubricant by spatial period interaction was not ($P=0.34$). Figure 7 shows a typical normal and tangential force trace from a single subject sweeping a finger across the lubricated and unlubricated 1.5-mm spatial period and the 8.5-mm spatial period surfaces. The RMS of the tangential force variations is indicated beside each trace. In this illustration the lubrication reduced the RMS of the tangential force of the 1.5-mm surface by 21.5% and the 8.5-mm surface by 25.4%. In contrast the mean coefficient of friction was reduced by 72% for the 1.5-mm spatial period and 45% for the 8.5-mm spatial period. Figure 8A graphically illustrates the mean normalized

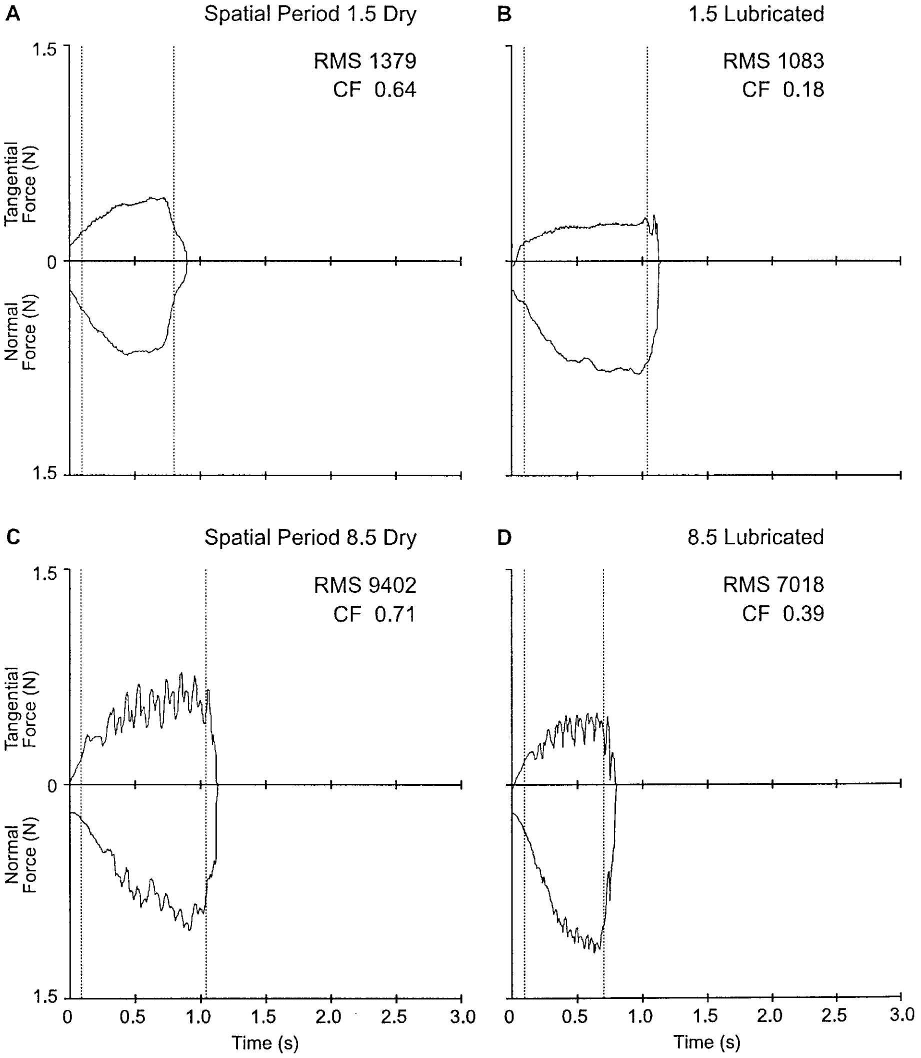


Fig. 7 Examples of the changes in the tangential force rate, dFx/d*t*, induced by lubrication for a single trial with the smallest (1.5-mm) and the largest (8.5-mm) spatial period. The *vertical dotted lines* show the period over which the RMS was calculated (*RMS* root mean square of the variations in tangential force, *CF* coefficient of kinetic friction for the trial illustrated)

RMS of the tangential force rate as a function of spatial period for lubricated and unlubricated surfaces for all six subjects.

The surface lubricant also significantly reduced the subjective roughness estimates made by the subjects for each of the eight surfaces by an average 16.4% ($F_{(1,80)}$=29.97, $P<0.001$). The spatial period was once again a significant main effect ($F_{(7,80)}$=70.00, $P<0.001$), but not the lubricant by spatial period interaction (P=0.45). Figure 8B illustrates the decrease in the normalized mean subjective roughness estimates for each of the surfaces. As one might expect, the effect of the lubricant was greater for the longer spatial periods. Taken together, the data obtained with surface lubrication provide persuasive evidence that the rate of variation in tangential force is an important, although perhaps not the sole, determinant of the subjective sensation of roughness during active touch. For example, examination of the results of individual subjects plotted in Fig. 9 indicates that changes in roughness estimates were not always associated with parallel changes in the rate of variation in applied tangential force. However, on average, variation in tangential force seems to be the best candidate to explain the subjective sensation of roughness.

Discussion

Mechanical determinants of roughness

The present study replicated and confirmed the earlier finding that the spatial period of surface asperities is an important component in the subjective scaling of roughness (Meftah et al. 2000; Sathian et al 1989; Taylor and Lederman 1975). Textured surfaces with widely spaced elements were perceived as rougher than those with narrowly spaced ones, because more skin was able to penetrate the space between the tactile elements. The mean normal and tangential forces, taken separately, had inconsistent correlations with subjective roughness estimates, showing that they were unreliable predictors of roughness magnitude. Although average friction, the ratio between mean tangential and mean normal force, was a better predictor of roughness, this measure did not ade-

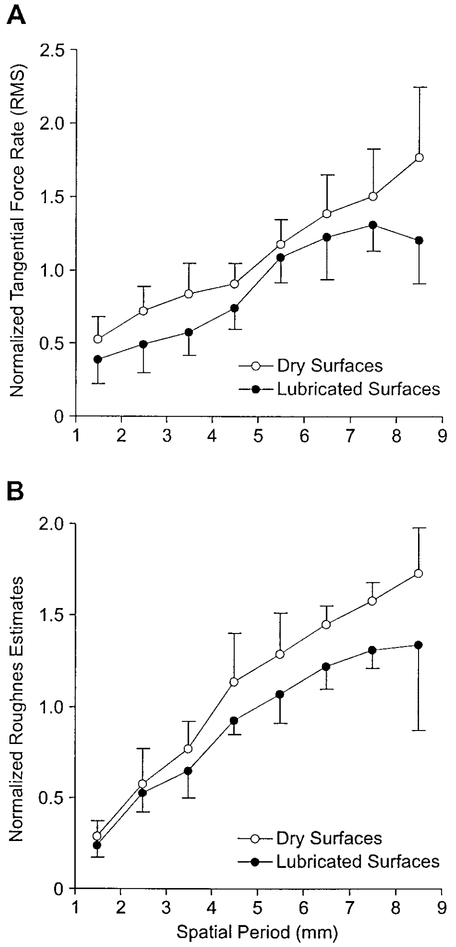


Fig. 8 **A** Mean normalized tangential force rate RMS (dFx/d*t*) averaged across the six subjects (± SD) for each of the lubricated and dry surface textures. **B** Mean normalized roughness estimates averaged across the six subjects (± SD) for each of the lubricated and dry surface textures

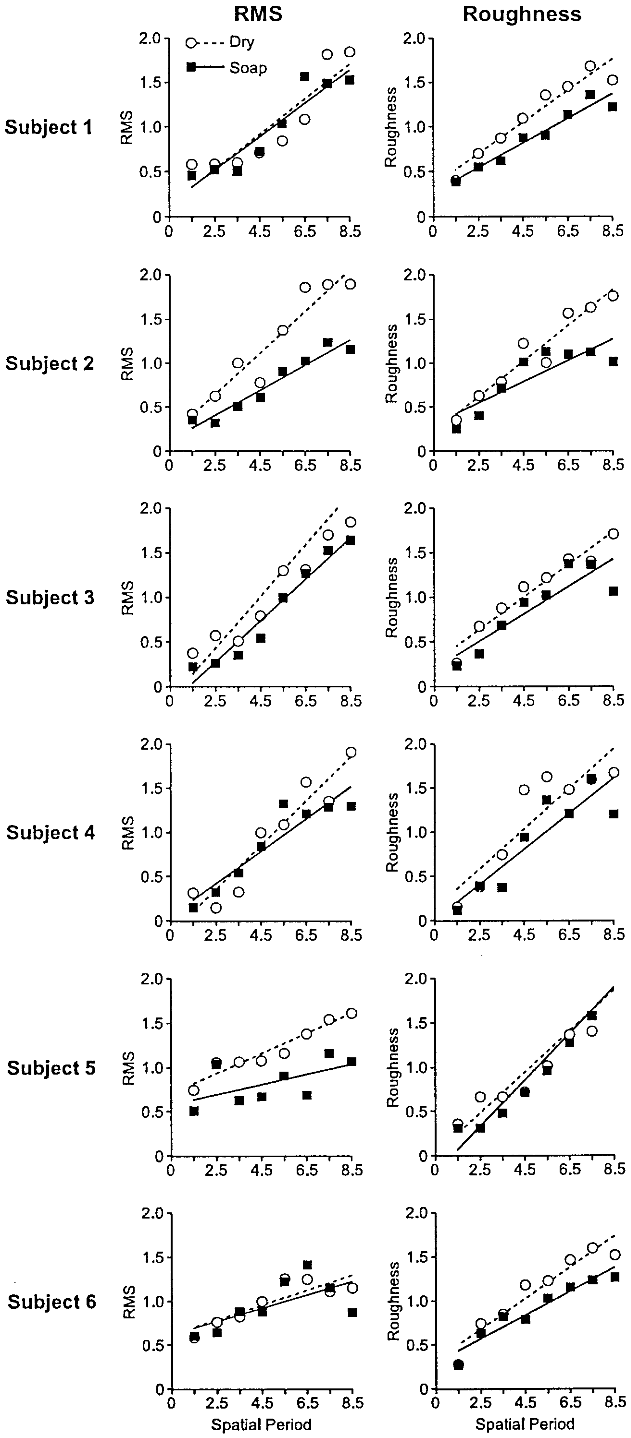


Fig. 9 Mean normalized variation in tangential force rate (RMS of dFx/d*t*) plotted as a function of spatial period (mm) during active scans with and without lubrication (respectively, soap and dry). Results from six subjects (experiment 2). For comparison, the mean normalized roughness estimates in the same conditions are also plotted (*right*)

quately describe the oscillations in the tangential force that accompanied the active scans. In addition, lubrication produced a 40% reduction in mean kinetic friction but only a 16% reduction in subjective roughness estimates. This latter value was closer to the 21% reduction in tangential force variation for the same conditions.

Instead, the results of the present study suggest that the rate of change in the tangential force (as quantified by the RMS) may be a more important parameter for roughness appreciation than mean kinetic friction. The RMS value correlated well with both the spatial period and the subjective roughness and provided stronger and more consistent correlations with roughness estimates than the mean friction. Furthermore, tangential force variations and subjective roughness were reduced about equally by lubrication of the test surfaces. Finally, relative differences between surfaces judged as smooth or rough were maintained across all subjects, despite substantial variations in the amount of tangential force applied to the test surface. Taken together, our results demonstrate that periodic fluctuations in tangential forces generated during active scanning of surfaces are an important determinant of the subjective sensation of roughness in humans. It seems very unlikely that subtle variations in hand kinematics contributed to the results, since all subjects showed similar relations between roughness and spatial period, independent of, for example, the scanning speed (Figs. 2, 6). Instead, we suggest that roughness reflects the instantaneous deformation profile of the skin, with wider spacing between the tactile elements leading to increased penetration of the skin between the rows of tactile elements and subsequently increased tangential drag.

The underlying biomechanics are likely to be complex. For example, Bisley et al. (2000) pointed out that when you touch a surface, there is a widespread distribution of stresses and strains over the compliant skin of the fingertip, and the underlying fingerpad, which can stimulate receptors remote from the area of immediate contact. The compliance of the fingerpad and the skin changes with the level of contact force. As a result, there are highly non-linear relations between the normal and tangential forces that constitute the coefficient of friction (Comaish and Bottoms 1971). These non-linearities are most evident at low contact forces, where the skin is most compliant. As the contact force increases, there is less local deformation as the tissues (fingerpad and skin) become more incompressable (Pawluk and Howe 1999). Moreover, the shearing stiffness also increases and the strain rate of the fingertip in the tangential direction is decreased (Nakazawa et al. 2000). From this one might have predicted that the scanning speed would substantially alter the distribution of stresses and strains over the finger, and yet paradoxically it has been shown that scanning speed has no effect on roughness estimates for the same surfaces as used in the present study (Meftah et al. 2000). Although a number of static biomechanical models of skin and the finger have been developed (Phillips and Johnson 1981; Srinivasan 1989), it is clear that these need to be further refined in order to explain more recent psychophysical results. In particular dynamic models such as those proposed by Nakazawa et al. (2000) and Nara et al. (2001) will be required in future.

Neural coding of roughness

Based on recordings from peripheral afferents innervating the glabrous skin of primates, Johnson and Hsiao (1992) suggested that at least two neurophysiological processes might be involved in the neural coding of roughness. One system, driven mainly by input from slowly adapting type I skin receptors (SAI), has a particularly high spatial acuity for discriminating relatively large single surface elements such as raised dots or grooved gratings. A second system, using input from rapidly adapting skin receptors (RA), has a lower spatial acuity than the SA system, but has a greater sensitivity to tangential shear generated by slip between the surface and the finger. This latter system would be more sensitive to discriminating degrees of smoothness such as the difference between plain and etched glass surfaces where the individual elements are indiscriminable. The results of the present study are consistent with this interpretation.

Connor and Johnson (Connor et al. 1990; Connor and Johnson 1992) made a concerted effort to determine whether roughness is determined by spatial or temporal variations in the firing rate of cutaneous mechanoreceptor afferents. In their first study, they found that a spatial variation model explained better their observed relations between roughness and spatial period – an inverted U-shaped curve that peaked at a ~3 mm spatial period and declined for further increases in raised dot spacing up to ~6 mm (corresponding to longitudinal spacings of, respectively, 4.5 and 8.8 mm). As discussed in Meftah et al. (2000), differences in the physical characteristics of the surfaces likely explain the discrepancy between our observation, confirmed here, of a roughly linear increase in roughness over the same range, and their observation of a decline at higher spacings. Subsequently, and using dot spacings restricted to the rising limb of their psychophysical curves, Connor and Johnson (1992) examined the effect of increasing the spatial period both in the direction of the scanning (the temporal direction) and orthogonal to the scanning motion (the non-temporal or spatial direction). As the dot spacing increased in the non-temporal direction, the temporal variations in mechanoreceptor firing decreased but estimates of roughness magnitude increased. From these observations, Connor and Johnson (1992) concluded that roughness sensation is based on spatial not temporal variations in mechanoreceptor firing rates. A spatial code is particularly interesting since it can explain why roughness estimates are constant over a range of scanning velocities (Lederman 1983; Meftah et al. 2000), despite the fact that the peripheral signals themselves covary with speed. According to the spatial variation hypothesis, differences in firing rates of afferents innervating skin regions separated by 1–2 mm are converted centrally into an intensive code that signals texture independent of the scanning conditions (Johnson and Hsiao 1992). Nevertheless, alternate mechanisms based on a mean firing rate code have been proposed (Chapman 1998; Williams et al. 1998; Meftah et al. 2000). In addition, several groups have since provided evidence that mean firing rate, and so temporal variation, is an important component of tactile roughness (Cascio and Sathian 2001; Gamzu and Ahissar 2001).

We believe that roughness perception is likely to require both a spatial and a temporal code. Spatial summation is automatically implicated by virtue of the fact that a minimum contact area between the skin and the surface is required in order to make any roughness estimations whatsoever. Nevertheless, the close correlations between the tangential force variations and roughness magnitude suggest that a temporal code, reflecting the amplitude of skin displacement, might also be involved. This suggestion is consistent with our observation that roughness declined with lubrication, even though the spatial characteristics of the textured surfaces were identical. Srinivasan et al. (1990) conducted one of the very few studies to examine mechanoreceptor discharge in response to tangential forces applied to the glabrous skin. Using a very smooth glass plate, they found that rapidly and slowly adapting afferents in the monkey hand only signaled the onset of slip over the skin surface. The initial response might have reflected a brief, transient fluctuation in the tangential force since further constant velocity motion failed to sustain continuous discharge. Consistent with the latter, Srinivasan et al. (1990) found that subjects cannot detect steady slip between the surface and the skin. The initial slip, on the other hand, is detectable, and Smith and Scott (1996) showed that this information is evidently sufficient to allow subjects to accurately scale smooth surface slipperiness.

Just as Katz proposed many years ago (Krueger 1970), the present study again raises the possibility that subjective sensations of roughness and smoothness may be in part a mechanoreceptor response to vibrations generated by fluctuations in the tangential forces on the skin. Figure 4 of the present study shows that smoother surfaces were associated with low-amplitude, high-frequency fluctuations in the tangential force whereas rougher surfaces were associated with high-amplitude, low-frequency tangential force variations. In contrast, Lederman (1985) has stated the opinion that vibration per se is not a primary determinant of roughness because roughness estimates are unaffected by a preceding vibrotactile adaptation. However, the evidence in our opinion is not compelling because the adaptation procedure (20 Hz or 250 Hz) would only have eliminated a small range of the frequency components generated during exploration of textured surfaces. According to Connor and Johnson (1992), the rapidly and slowly adapting glabrous skin mechanoreceptors are collectively sensitive to vibrations over a range from 0 to 500 Hz. Further testing of this hypothesis is clearly required.

Bisley et al. (2000) noted that single primate SAI afferents innervating the sides and the end of the finger responded to tangential forces applied to the middle of the distal pad of the finger. Although Bisley et al. suggested that these afferents might play a role in determining tangential forces on the digits during object manipulation, they might equally well provide a neural basis for roughness estimation. From microneurographic studies in human subjects, Berzneiks et al. (2001) found that all of the large fiber, rapidly and slowly adapting, mechanoreceptors of the fingertip skin were sensitive to the application of lateral or tangential forces. Furthermore, many receptors responded to tangential forces in only one of two opposite directions. It seems plausible that these same mechanoreceptors would be particularly sensitive to the RMS of the tangential force rate and consequently provide a neural basis for the encoding of roughness.

As noted at the outset, roughness is an emergent mental quality determined by a number of physical parameters and synthesized from several cutaneous afferent types. The truncated cones used both in the present study were much higher (1.8 mm) than the 0.35-mm raised dots used by Conner and Johnson (Conner et al. 1990; Conner and Johnson 1992), which may explain why roughness failed to peak at a spatial period of about 3 mm. If the sensation of roughness were a reflection of tangential force variation as we are suggesting, we would predict that reducing the asperity height from 1.8 mm to 0.35 mm should produce a damping of the RMS of the tangential force and the subjective roughness in a manner similar to the effect of lubrication. In fact, changes in the feature spacing, height, form and softness would all contribute to variations in tangential force in dynamic touch and therefore should ultimately influence the perception of roughness.

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