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Roughness of simulated surfaces examined with a haptic tool; effects of spatial period, friction, and resistance amplitude.

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Abstract

A computer controlled force-feedback device simulated textures consisting of modulated resistances to lateral motion. The textures were either periodic trapezoidal force fields, or modulated sinusoidal forces spaced at various intervals from 1.5 mm to 8.5 mm. In each of two experiments, ten subjects interacted with the virtual surfaces using the index finger placed on a mobile plate that produced the lateral force fields. The subjects selected their own speed and contact force for exploring the test surface. The apparatus returned force fields as a function of both the finger position and finger normal force allowing full control over the tangential interaction force. In experiment #1, subjects used an integer, numerical scale of their own choosing to rate the roughness of eight identical, varyingly-spaced force ramps superimposed on a background resistance. The results indicated that subjective roughness was significantly, but negatively, correlated with spatial period (mean $r = -0.84$) of the resistances for all subjects. In a second experiment, subjects evaluated the roughness of 80 different sinusoidal modulated force fields, which included 4 levels of resistance amplitude, 4 levels of baseline friction, and 5 spatial periods. A multiple regression procedure indicated that the coefficient of friction and the tangential force amplitude together produced a combined correlation of 0.70 with subjective roughness. The addition of spatial period only increased the multiple regression correlation to 0.71. The correlation between roughness estimates and the rate of change in tangential force was 0.72 in experiment #1 and 0.57 in experiment #2. The results suggest that the sensation of roughness is strongly influenced by friction and tangential force amplitude, whereas the spatial period of resistance alone makes a negligible contribution.

Introduction

In an effort to establish objectively quantifiable surfaces for the purpose of studying the subjective sensation of roughness, many investigators resorted to using surfaces with precisely controlled gratings or 2-dimensional raised dots or truncated cones. These manufactured surfaces with periodically spaced elements could be characterized in terms of the ridge or groove width or inter-dot spacing and height. Lederman and Taylor (1972) were one of the first to note that for engraved linear metal gratings, the groove width between the ridges exerted a greater effect on perceived roughness than the ridge width. This observation has since been repeatedly confirmed (Cascio and Sathian 2001; Lederman 1974; Sathian et al., 1989), and consequently it appeared that the sensation of roughness increased monotonically with increasing groove width, whereas an increase in ridge width tended to decrease the roughness. A similar observation was made using 2-dimensional raised trapezoidal asperities. Both Connor et al. (1990) and Meftah et al. (2000) found a monotonic relationship between roughness and spatial period up to an inter-element spacing of at least 3.0 mm.

Smith et al., (2002) interpreted this observation as suggesting that, as the groove width increased, more fingertip skin was deformed during the scanning process, increasing the lateral force necessary to drive the finger forward over the test surface and consequently increasing both the tangential resistive force and the average coefficient of friction. Their data demonstrated that the tangential force increased with the spatial period whereas the normal or contact force remained unchanged. Connor *et al.* (1990) and Klatzky *et al.* (2003) suggested that the relationship between the inter-element spacing and subjective roughness was best described by an inverted “U” or quadratic function best, because as the spatial period further increases, the surfaces begin to feel smoother.

The neurophysiological mechanisms fundamental to the sensation of roughness has been the subject of considerable research. Generally, this research has focused on the spatial period as the primary parameter causing the sensation of roughness because the activity of single skin mechanoreceptors increases monotonically with spatial period up to certain limits determined by the particular height of the ridge or asperity. (Bensmaïa et al 2006; Blake et al 1997; Conner et al 1990; Conner and Johnson 1992; Yoshioka et al 2001). However, the physical parameters associated with asperity height and spacing contributing to the sensation of roughness are still unclear. As a result, there has been a trend away from studying topological features such as the spatial period and asperity height and instead the dynamic aspects of skin stimulation have received more recent emphasis (Nakazawa et al., 2000; Smith and Scott 1996; Smith et al 2002; Yoshioka et al 2007). Smith et al (2002) suggested that variations in the tangential scanning force could be an important determinant of subjective roughness and a more recent study by Yoshioka et al (2007) made a similar suggestion that changes in lateral scanning acceleration or "vibratory power" was also correlated with the sensation of roughness.

There have been several attempts to use computer-controlled haptic devices such as the PHANToM (Wall and Harwin 2000; Kornbrot et al 2007) or other devices (Minsky and Lederman 1996) to simulate roughness of virtual surfaces. Although these devices cannot adequately render the spatial pattern of skin indentation of particular textures, they can adequately simulate spatio-temporal pattern of lateral strain encountered during tactile exploration. In this regard, computer-controlled haptic devices simulate indirect tactile exploration through an interface such as a glove or probe. Klatzky and Lederman (2006) examined the roughness scaling of simulated textures consisting of alternating regions of high resistance (simulated ridges) and low resistance (simulated grooves) using a computer mouse providing force-feedback. They reported that roughness magnitude increased with the duration of the resistance for spatial periods ranging from 0.08 to 7.99 mm.

Although the experiment by Klatzky and Lederman (2006) demonstrated that the resistance variations of a surface contribute to the sensation of roughness, the variations in the spatial period were not distinguished from either the amplitude of the tangential resistance force or the coefficient of friction. Moreover, other studies using simulated textures found the relationship between roughness estimates and the spatial period of resistance to be inconsistent and statistically unreliable (Campion et al 2008; Wall and Harwin 2000). In the study by Smith et al (2002), using real surfaces, subjective roughness increased with both the amplitude of tangential force and the spatial period, whereas the frequency of tangential force changes decreased. This discrepancy raises the question as to how the spatial period is related to the sensation of roughness when dissociated from the tangential force amplitude and friction.

A recent pilot study by Campion et al (2008) indicated that with sinusoidal resistances simulated by modulated friction, the perceived roughness was strongly correlated with both the amplitude of force modulation and the coefficient of friction but that the relation to spatial period was inconsistent. The aim of the present study was to examine the roughness scaling of computer-simulated surfaces by varying the spatial periods of resistance, coefficient of friction and tangential force amplitude independently.

Materials and Methods

Force-feedback, haptic apparatus

The haptic apparatus, illustrated in Figure 1, was composed of a mobile exploration plate supported by two articulated arms linked to two torque motors, each equipped with high-resolution optical angle position encoders. Together, these motors could generate controlled tangential force fields opposing the lateral motion of the finger as a function of the position in the 6 cm x 10 cm workspace and thereby generate the illusion of a variety of 3-dimensional, virtual surfaces. A strain gauge, located beneath the workspace, measured the force exerted on the plate normal to the fingertip surface (F_n), which was used by a computer to adjust the tangential resistance and control the coefficient of friction in real time. The force feedback device was able to render the virtual gratings adequately within the force range employed by the subjects in the present experiment. That is, the horizontal temporal determinants of texture were rendered without distortion by the inertial properties of the apparatus.

Task

The task for the subjects in both experiment #1 and #2 was the same. All subjects were informed that they were to participate in an experiment evaluating the subjective scaling of roughness. The subjects were seated comfortably in a chair with the right forearm fastened at the elbow and wrist to a padded armrest to limit movement of the wrist. All subjects wore a sound-attenuating ear protector to eliminate auditory cues and a cap, which completely occluded vision of the apparatus. After the subjects were read the instructions, they were allowed a practice period to familiarize themselves with using the apparatus to explore several different simulated textures. The subjects were free to exert the contact force and employ the scanning speed of their own choosing throughout the experiment. On each trial the subject started with the finger at the extreme left of the workspace and, on a signal from the experimenter, the subject made two complete sweeps (from left to right and-right to left, twice) across the simulated texture.

Simulated surface textures:

The haptic device was programmed to generate the illusion of uniform textured surfaces throughout the workspace by a range of position-modulated resistive forces as the subject moved the finger plate from left to right or right to left. Although all subjects reported feeling skin indention, in fact, there was no vertical movement whatsoever. The tangential or lateral resistive forces were calculated as a function of the finger position and the normal contact force exerted on the mobile plate. The subject encountered a unidirectional resistance force generated according to the function:

$$F_t = \mu \cdot (1 + A \cdot h(x)) \cdot F_n$$

where μ is the coefficient of friction, A is the depth of modulation of the tangential force, h(x) is the friction modulation profile (trapezoidal in Experiment #1 sinusoidal in Experiment #2), and F_n is the normal force exerted by the subject on the contact plate.

Experiment #1

Subjects

A total of 10 healthy, right-handed subjects (6 men and 4 women) between the ages of 18 and 35 without motor or sensory impairment to their right hand participated in Experiment #1. All subjects signed an informed consent form, which had been approved by the medical faculty ethics committee of the Université de Montréal.

Force profile

In Experiment #1, we created trapezoidal force fields, illustrated in Figure 2, with variable inter-resistance spacings that were intended to mimic the truncated cones used by Meftah et al. (2000) and Smith et al (2002). However, our force-feedback device was unable to generate the very high coefficients of friction (mean μ = 1.3) created by the 1.8 mm high, truncated cones used in this earlier study. Instead, the simulated surfaces in the present study had a much lower, but more commonly encountered average modulated coefficient of friction (μ = 0.35 ±0.02), which was a controlled variable for all the simulated surfaces in the present study. The highest friction was encountered when the virtual interaction point reached the "plateau" of the truncated cone shape, and the least friction was encountered with the plane surface supporting the simulated cones. The coefficient of friction (μ) is the ratio of the normal (F_n), to tangential force (F_t), and therefore, since each subject was actively scanning, the tangential force was adjusted in real time according to the normal force exerted by the subject as well as the position of the finger in the work space. The simulated truncated cones are shown in Figure 2A which depicts a series of stimuli for spatial periods of resistance varying from 1.5 mm to 8.5 mm. The trapezoidal resistance force fields in experiment #1 differed only with respect to their inter-resistance spacings or spatial period.

Each subject was presented with five random replications of eight spatial periods for a total of 40 trials. Each subject made two complete sweeps across the workspace following which they were asked to estimate the numerical magnitude of the roughness of the surface using an integer numerical scale of their choosing. The numerical estimates used by each subject were later normalized to facilitate rating comparisons between subjects. The normalized scores were calculated by subtracting the subject's mean score from each raw estimate and dividing by the standard deviation of the subject's estimates.

Results

Figure 3 shows the normal and tangential forces on single trials from a single subject scanning the trapezoidal force fields with spatial periods ranging from 1.5mm to 8.5mm indicated above each of the eight images. In each of the eight panels, the lower trace (shown in blue) indicates the normal contact force exerted by the subject on the exploration plate. The mean normal or contact force was 1.54 N, ±0.50, which is about 1.0 N greater than the force used to explore smooth real surfaces, probably because the subjects were aware they were exploring the test surfaces with a flat disk interposed between the finger and the test surface. The modulated tangential force fields simulating the asperities are shown in red. Notice that the tangential force amplitude does not increase with the greater element spacing as would be the case with a real texture where more skin penetrates the inter-asperity spacing increasing the lateral resistance amplitude (see Figure 4, Smith et al 2002). Although the amplitude of lateral resistance was invariant, the temporal grouping varied as a function of the subject's exploration speed, which explains the different lengths of the traces. The green trace in Figure 3 shows the first derivative or rate of tangential force change (dF_t/dt) Together, these force traces help visualize the haptic sensations encountered by the subjects. When the F_t was increasing, the subjects had the impression they were ascending a physical obstacle, when the F_t was decreasing the subjects had the impression they were descending a physical slope. Since our previous study with real surfaces (Smith et al 2002) indicated that subjective roughness increased with the spatial period of the asperities, it was somewhat surprising that the subjective roughness actually *decreased* monotonically. Figure 4 illustrates this inverse relationship between the normalized roughness ratings and the spatial periods for the 10 subjects. The correlation coefficients were statistically significant and ranged from $r = -0.70$ to $r = -0.91$ with a mean of $r = -0.84$ ($n = 40$, $p<.001$). The correlations for the individual subjects are shown in Table I.

For real textured surfaces, Smith et al (2002) found that tangential force variations as measured by the root mean square of the tangential force derivative (dF_t/dt RMS) increased with the spatial period and was strongly correlated with roughness. Therefore, we examined the relationship between the normalized rate of tangential force change and the normalized roughness estimates. Since the tangential force was modulated according to the normal force exerted by subject on the surface, both the dF_t/dt RMS and the roughness estimates were normalized to allow comparisons between subjects. These results are shown in Figure 5, and Table 1. They indicate that the normalized tangential force variations were inversely correlated with the spatial period of the resistances, which were very similar to the normalized roughness estimates. The correlations ranged from -0.63 to -0.85 with a mean negative correlation of -0.80 ($p<0.001$)

Since both the dF_t/dt RMS and spatial period were inversely correlated with the subjective roughness, it was logical to assume the correlation between dF_t/dt RMS and subjective roughness would therefore be positive. The correlation between normalized roughness estimates and the normalized dF_t/dt RMS for the 10 subjects together is shown in Figure 6. The correlations for individual subjects ranged from 0.60 to 0.90 with a mean of 0.72 ($p<0.001$).

At the conclusion of experiment #1, we were concerned that the notion of roughness as distinct from spatial period might have been confusing or ambiguous for our subjects. Consequently, we selected a new group of 10 naïve subjects and asked them to numerically rate each of our stimuli based on the subjective estimate of the spatial period of resistance. The correlation coefficients were both positive and statistically significant for each of the subjects. The mean was 0.83 and the correlations ranged from $r=0.60$ to $r=0.94$ ($p<0.001$) and the group data are shown in Figure 7. From this additional study, we concluded that the subjects were able to adequately perceive and rate the spatial period as distinct from the sensation of roughness.

Discussion Experiment #1

The principal finding of Experiment #1 was that the roughness estimates of the trapezoidal ridges simulated by force feedback were negatively correlated with the spatial period of the inter-element spacing. This does not contradict the several earlier studies showing positive correlations, but instead demonstrates that a positive relationship between roughness and spatial period is only observed if the tangential forces increase with the spatial period. When the tangential force remains constant, the correlation is negative. This is consistent with the several earlier studies showing that using a probe, subjective roughness increased with the spatial period only if the probe was not able to penetrate to the bottom of the grooves between ridges (Klatzky and Lederman 1999; Klatzky *et al.* 2003; Hollins *et al.* 2004, 2005, 2006). The results of experiment #1 are also consistent with those obtained from direct exploration by Connor et al (1990), as well as indirect exploration with a tool by Klatzky et al (2003) describing the relationship between roughness estimates and spatial period as an inverted “U” or quadratic function. Although studies of direct exploration with the fingertip have emphasized the positive correlations between the intensity of subjective roughness and the spatial period of the asperities, (Lederman and Taylor 1972; Taylor and Lederman 1975; Sathian *et al.* 1989 ; Meftah *et al.* 2000 ; Smith *et al.* 2002), these studies may not have tested a sufficient range of inter-element spacings to observe the full quadratic function. It appears that roughness perception increases as long as the exploratory probe (finger or tool) encounters increasing tangnetial force. Roughness becomes inversely proportional to spatial period from the point that the probe or finger encounters decreased resistance associated with the flat surface between the resistive elements. Since in the present study, the probe “tracked” the entire surface, only the second part of this quadratic relationship was observed.

A negative correlation between increasing spatial period and roughness for synthetic surfaces was also found by Korbrot *et al.* (2007) using the PHANToM® haptic device to simulate textured surfaces using tangential force modulation to simulate inter-element periods between 0.7mm and 20.7mm. Although Klatzky and Lederman (2006), found that roughness increased with spatial periods ranging from 0.08 mm to 7.99 mm, the workspace in their study was very small (2.2 x 1.8 cm).

Campion et al (2008) suggested the reason for the discrepancies between Klatzky and Lederman (2006) and Korbrot *et al.* (2007) was due to the confounding influences of resistance amplitude and friction. That is, the effect of spatial period was masked by variations in the amplitude of perturbations and fluctuations in friction. For this reason, our force feedback device was programmed to produce surfaces with standardized changes in friction (mean friction = 0.22) and uniform tangential force amplitudes (i.e. 1.0 N superimposed on a constant resistance of 0.5 N) for a range of spatial periods. In the present study, the force feedback device emulated exploration with a probe, but the tangential force field amplitude did not increase with the increased element spacing as shown by the uniform tangential force perturbations (the red trace) in Figure 3. In our opinion, the homogeneous perturbations and identical friction profiles account for the negative correlation between spatial period and roughness estimation shown in Figure 4. The relative impact of resistance amplitude and coefficient of friction and their interaction with the spatial period were examined in experiment #2.

Experiment #2

Subjects

Ten additional naive healthy, right-handed, men (6), and women (4), between the ages of 18 and 35, participated in experiment #2. Again, all subjects signed an informed consent form, which had been approved by the medical faculty ethics committee of the Université de Montréal.

Force profiles

In experiment #2, the haptic device was programmed to generate uniform textured surfaces modeled as spatially modulated sinusoidal friction gratings explored using the finger plate as a probe. Like experiment #1, the tangential forces were adjusted in real time according to the normal force exerted by the subject and the position of the finger in the work space. In this experiment, we investigated the effects of friction, force modulation amplitude, and spatial period within a single study using the sinusoidal resistance pattern (Figure 2B) developed by Campion et al (2008). The amplitude modulation applied to the sinusoid was a variable percentage of the coefficient of friction. The amplitude modulation was intended to simulate the physical height of the asperities above the background surface whereas the spatial period represented the distance between the successive maxima for the sinusoidal wave. The sinusoidal resistance wave shape used in this study is also shown in Figure 2. For experiment #2, the profile $h(x) = \sin\left(\frac{2 \cdot \pi \cdot x}{l}\right)$ was used (Campion et al 2008). In total, 80 different textures were simulated with 4 levels of friction (μ=0.1; 0.2; 0.3; 0.4), 4 levels of resistance modulation (*A*=0.25; 0.5; 0.75; 1.0), and 5 spatial periods (*l*=1.0, 2.0, 3.0, 4.0, 5.0 mm). Each subject was presented with each of the 80 surfaces 5 times in random sequence for a total of 400 trials.

Results

In order to assess the relative contribution of friction, tangential force amplitude and spatial period to roughness estimation, a multiple regression analysis was applied to the data. Table II shows that friction (partial r=0.61) and tangential force amplitude (partial r=0.41), emerged as the principal parameters producing a combined multiple regression coefficient of 0.70 (P<0.01). Spatial period alone had a negligible correlation with roughness (r=0.09, P<0.05) and the addition of the spatial period of resistance only increased the average multiple regression to 0.71 from 0.70. Table III shows the correlations for individual subjects. Figure 8, graphically illustrates relationships between friction and tangential force modulation and the roughness estimates for the 10 subjects grouped together in a three-dimensional diagram. Figure 8A shows that mean friction made a greater contribution to roughness estimates than the spatial period. Figure 8B shows the mean contribution of spatial period and amplitude of tangential force modulation to the roughness estimates. The slope of the spatial period of resistance is nearly flat indicating its negligible impact on roughness estimates compared to the slope of the tangential force modulation. Similarly, Figure 8C shows that friction makes a slightly greater contribution to roughness estimation than the amplitude of tangential force modulation. Overall, the spatial period had no consistent relationship with the roughness estimates whereas both friction and tangential force modulation had strong monotonic relationships.

Since our previous study of real textures indicated that the mean rate of tangential force change (dF_t/dt RMS) was strongly correlated with roughness estimates (Smith et al., 2002), we next examined the correlation between the normalized dF_t/dt RMS and the normalized roughness estimates. Normalization of the dF_t/dt RMS was necessary because the absolute lateral resistance was calculated for each subject on each trial as a function of the subject's pressure on the exploration plate. Normalization was achieved by dividing each raw estimate by the subject's mean score. Unfortunately, for two subjects, the tangential force data were lost due to a computer failure, and consequently, Figure 9 shows the correlations between the normalized roughness estimates and the normalized dF_t/dt RMS for only 8 subjects. That is, the 5-trial average rating for the 80 surface textures for the 8 subjects yielded a total 640 data points. The correlation coefficient between the normalized dFt/dt RMS and the normalized roughness estimate ($r = 0.57$) although statistically significant ($p<.001$), was not as high as the combined effects of friction and the tangential force amplitude ($r = 0.70$).

Discussion Experiment #2

Experiment #2 modeled surface textures as modulated sinusoids explored with a probe, in order to reveal the separate effects of friction, resistance amplitude and spatial period on roughness sensation. The results from the multiple regression analysis indicated that friction made the largest contribution to roughness sensation ($r = 0.61$) accounting for 37% of the variations in roughness estimates. The depth of tangential force modulation was also a significant, parameter but with a smaller impact ($r = 0.34$) accounting for 12% of the variations in roughness estimates. It should be noted however, that the friction and tangential force modulation are not entirely independent. In this experiment, the amplitude was expressed as a percentage of the baseline friction meaning that a 0.2 amplitude of a $\mu = 0.1$ friction baseline has the same maximal Ft value as a 0.1 amplitude of a $\mu=0.2$ friction baseline. The baseline friction has a double impact, on both the mean friction and on the maximal friction by the amplitude's multiplicative value. The spatial rate of change of the tangential force amplitude is also an important component of both parameters. That is, doubling the coefficient of friction and halving the amplitude modulation does not change the maximum lateral force or the spatial derivative of the lateral force, although the mean lateral force felt by the subject would be doubled in this case.

General Discussion

Admittedly, the physical determinants of roughness have yet to be conclusively elucidated. However, the force-feedback device used in the present experiment allowed us to examine the tactile exploration of computer-generated virtual textures much as one would use a tool to probe a surface composed of evenly spaced trapezoidal or sinusoidal asperities. With this apparatus, we have been able to isolate, and independently vary, physical properties such as asperity type, coefficient of friction, amplitude and spatial frequency of resistance. By controlling these parameters, we demonstrated that the lateral forces deployed in haptic exploration play an important role in roughness perception. Yoshioka et al (2001, 2007) and Hollins and Risner (2000) have shown that stickiness and roughness are dissociable perceptual dimensions. Since stickiness is associated with both friction and tangential force, one might ask how do the determinants of stickiness and roughness differ? Obviously, we have no difficulty in distinguishing a sticky smooth surface from a rough textured surface. A sticky surface will have a very high initial coefficient of static friction, but once the initial adhesive bond has been broken, the coefficient of kinetic friction will be considerably lower. The same is true for a merely rough surface but to a much lesser degree. The essential difference probably lies in the spatio-temporal stick-slip pattern of adhesion to the skin.

Despite the fact that we used only modulated resistances to lateral movement throughout the present study, our subjects consistently believed they felt raised asperities as they explored the test surface with the fingerplate. Moreover, a separate group of subjects were able to identify and scale the spatial period of these same surfaces. From these observations, we conclude that the illusion of exploring a real texture with a tool was successful simulation.

Nevertheless it is worth considering what constitute the major differences between roughness examined using computer-generated simulations compared to real textures. That is, to what extent do the perceptual properties of our virtual surfaces mirror those of real surfaces? Primarily, the finger disk was unable to render the spatial pattern associated with a texture impressed on the skin; much like a glove or a shoe filters sensations for the hand or foot. Virtual surfaces simulated by lateral force feedback appear to able to capture the basic elements of roughness and would seem to be limited mainly by the ability of the probe to resolve the spatial arrangement of the surface elements (Hollins *et al.* 2004, 2005, 2006; Klatzky and Lederman 1999; Klatzky *et al.* 2003; Korbrot *et al.* 2007; Wall and Harwin 2000; Yoshioka *et al.* 2007)

However, static touch with the finger stationary and no tangential performs poorly at roughness estimations whereas the moving finger in active touch is superior at detecting changes in the flow of lateral forces on the skin. Johnson and colleagues (Blake et al 1997; Conner et al 1990; Conner and Johnson 1992), demonstrated the effects of moving different surface textures at

40mm/s both on subjective roughness estimates and on the discharge pattern of skin mechanoreceptors. However, an analysis of how each of these surface textures affected the pattern of tangential forces on the skin was never undertaken. Nevertheless, Birzneiks et al (2001) has shown that all the major classes of large-fibre skin afferents respond to forces applied to the skin at a 20-degree tangent, as well as forces applied normal to the skin surface.

In experiment #1 and in an earlier study, Smith et al (2002), found that the rate of change in tangential force was highly correlated with roughness estimates for surface asperities varying in spatial period. However, in the present study, the tangential forces were a product of a computer algorithm and the dF_t/dt RMS was merely the mathematical derivative of the programmed friction, resistance amplitude, and spatial period, which could be calculated for each surface. Although the correlation of the dF_t/dt RMS with roughness estimates revealed a significant relationship ($r = 0.57$, $P<0.05$), this was not entirely unexpected, since the rate of change was calculated from the tangential force amplitude and therefore was not an independent parameter. However, experiment #2 indicated that tangential forces on the skin, whether expressed as an amplitude, a rate derivative or as a ratio with normal force (i.e. friction), make an important contribution to roughness estimates, whereas the spatial period of resistance does not. The modulation of tangential forces probably accounts for the many studies showing that subjective roughness increases monotonically with the spatial period. Lederman *et al.* (1999) and Yoshioka *et al.* (2007) expressed some doubt that variations in scanning force and velocity could account for variations in the sensation of roughness since fluctuations between individuals had little effect on roughness estimation over a range of moderate contact forces and exploration speeds. Nevertheless, Yoshioka *et al.* (2007) found that “vibratory power” was the physical parameter that was best related to roughness. The emphasis on vibration presumably refers to the frequency of skin indentation whereas dF_t/dt RMS refers to the rate of force application to the

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skin. The term *vibratory power* used by Yoshioka *et al.* (2007) does not differ greatly from the root mean square of the rate of force change suggested by Smith et al (2002). Essentially the tangential force amplitude has greater power with the dFtan RMS compared to vibratory power.

These observations collectively suggest a rather simple interpretation. Roughness perception is driven by the rate of mechanical activation of the mechanoreceptors when a scanning a surface (hence the term "power" is quite apt), together with a perceptual constancy mechanism able to compensate for the effect of speed (Meftah et al 2000; Dépeault et al 2008). These findings also support the notion that the brain does not rely on the estimation of overly simplified geometrical quantities such as spatial period to gauge the roughness of a surface, but infers the possible existence of complex geometries for the touched surface at a level of detail that far exceeds the static spatial discrimination capacities of the skin. This interpretation is consistent with the prior findings indicating that texture perception is relatively unaffected by the use of tools or probes.

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Table I. Correlations between spatial period and roughness estimates

Correlation coefficient											
Subject	1	2	3	4	5	6	7	8	9	10	Mean
Correlation	-0.82	0.91	-0.82	-0.70	-0.91	-0.84	-0.76	-0.83	-0.87	-0.90	-0.84*

* = P<0.001

Table II. Multiple regression of parameters influencing roughness estimates

Parameter	Partial correlations	**P**
Friction	0.61	<0.001
Amplitude	0.34	<0.001
Spatial period	0.09	<0.001
Correlation coefficient (*without spatial period*)		$R_{multiple}$ = 0.70*
Correlation coefficient (*with spatial period*)		$R_{multiple}$ = 0.71*

* = P<0.001

Table III. Multiple regression of amplitude and friction with roughness estimates for each subject

Correlation coefficient											
Subject	1	2	3	4	5	6	7	8	9	10	Mean
Without SP	0.82	0.57	0.75	0.57	0.77	0.72	0.67	0.82	0.85	0.57	0.70*
With SP	0.82	0.62	0.75	0.82	0.77	0.72	0.67	0.82	0.85	0.57	0.71*

* = P<0.001

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Figure legends

Figure 1 **A)** The computer controlled force-feedback device side view. Note that the finger plate does not contact the work surface. **B)** The computer controlled force-feedback device seen from above. **C)** The alternating force fields depicted as black and white stripes seen from above.

Figure 2 **Above;** the trapazoidal force field. **Below;** the sinusoidal force field.

Figure 3 The normal and tangential forces on single trials from a single subject over spatial periods ranging from the 1.5 mm to 8.5mm. The normal forces are shown in blue and the tangential force is shown in orange. The first derivative or tangential force rate (dF/dt) is shown in green.

Figure 4 Correlations between normalized subjective roughness and spatial period for each of the 10 subjects. The solid thick line represents the linear regression whereas the thin line represents the normalized mean roughness estimate for each spatial period.

Figure 5 Correlations between the normalized first derivative or tangential force rate (dF/dt) and spatial period for each of the 10 subjects. As in Figure 4, the solid thick line represents the linear regression whereas the thin line represents the normalized mean roughness estimate for each spatial period**.**

Figure 6 Correlations between the normalized first derivative or tangential force rate (dFtan/dt) and normalized roughness ratings for each of the 10 subjects. The solid thick line represents the linear regression whereas the thin line represents the normalized mean roughness estimate for each spatial period.

Figure 7 Correlations between the normalized estimates of the spatial period and the actual spatial period for each of the 10 subjects. The solid thick line represents the linear regression whereas the thin line represents the normalized mean roughness estimate for each spatial period.

Figure 8 Shows the interrelationship between friction, tangential force amplitude, and spatial period and subjective roughness. The upper portion of Figure 8 illustrates the strong influences of friction and tangential force amplitude on subjective roughness changes. The middle part of Figure 8 shows weak relation of spatial frequency to subjective roughness compared to friction. The lower part of Figure 8 again show shows the weak relation of spatial frequency to subjective roughness compared to tangential force amplitude.

Figure 9 Relation of normalized roughness estimates to normalized RMS of tangential force.

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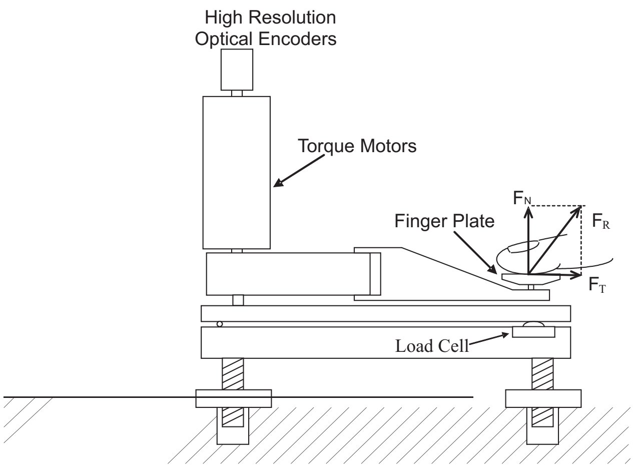
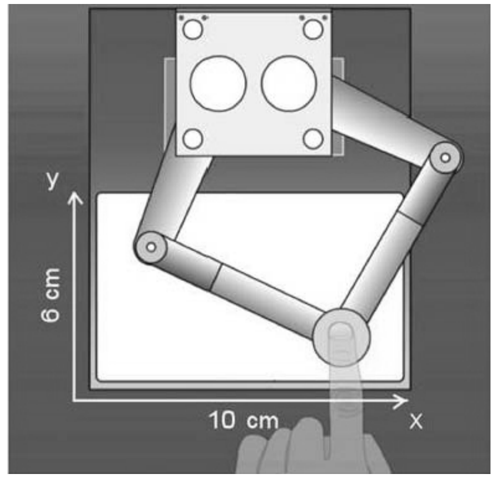
Figure 1

A



B



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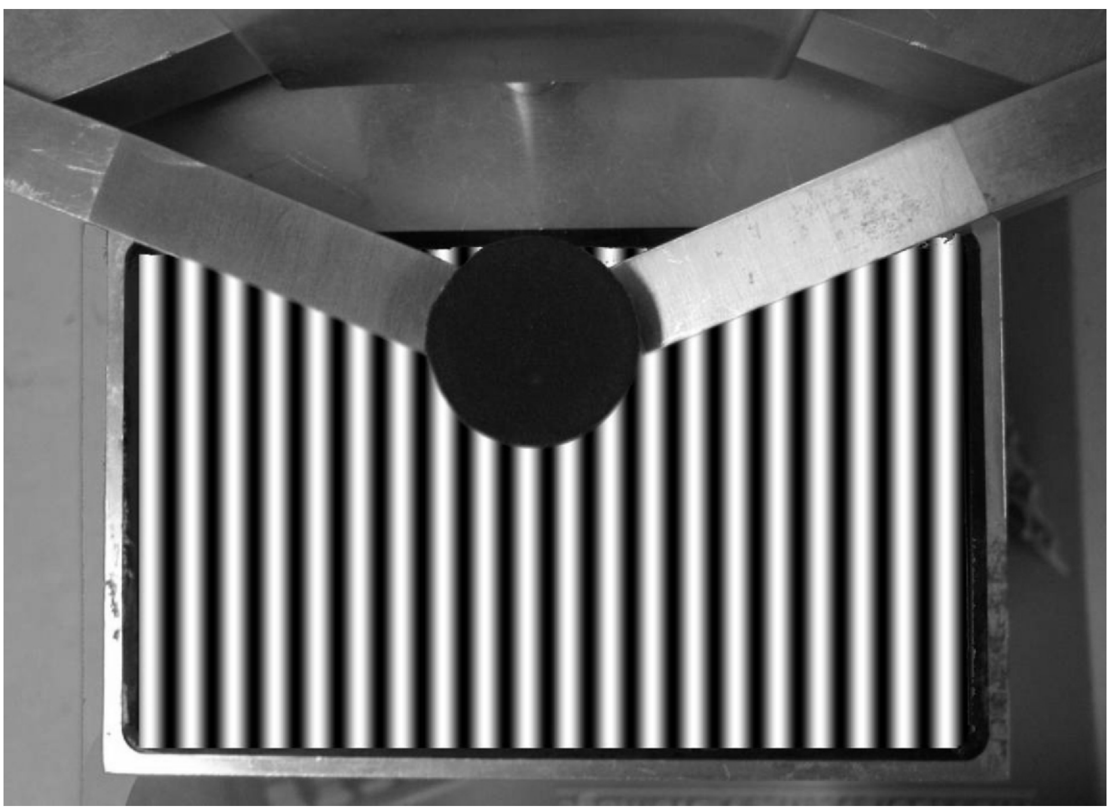

Figure 2

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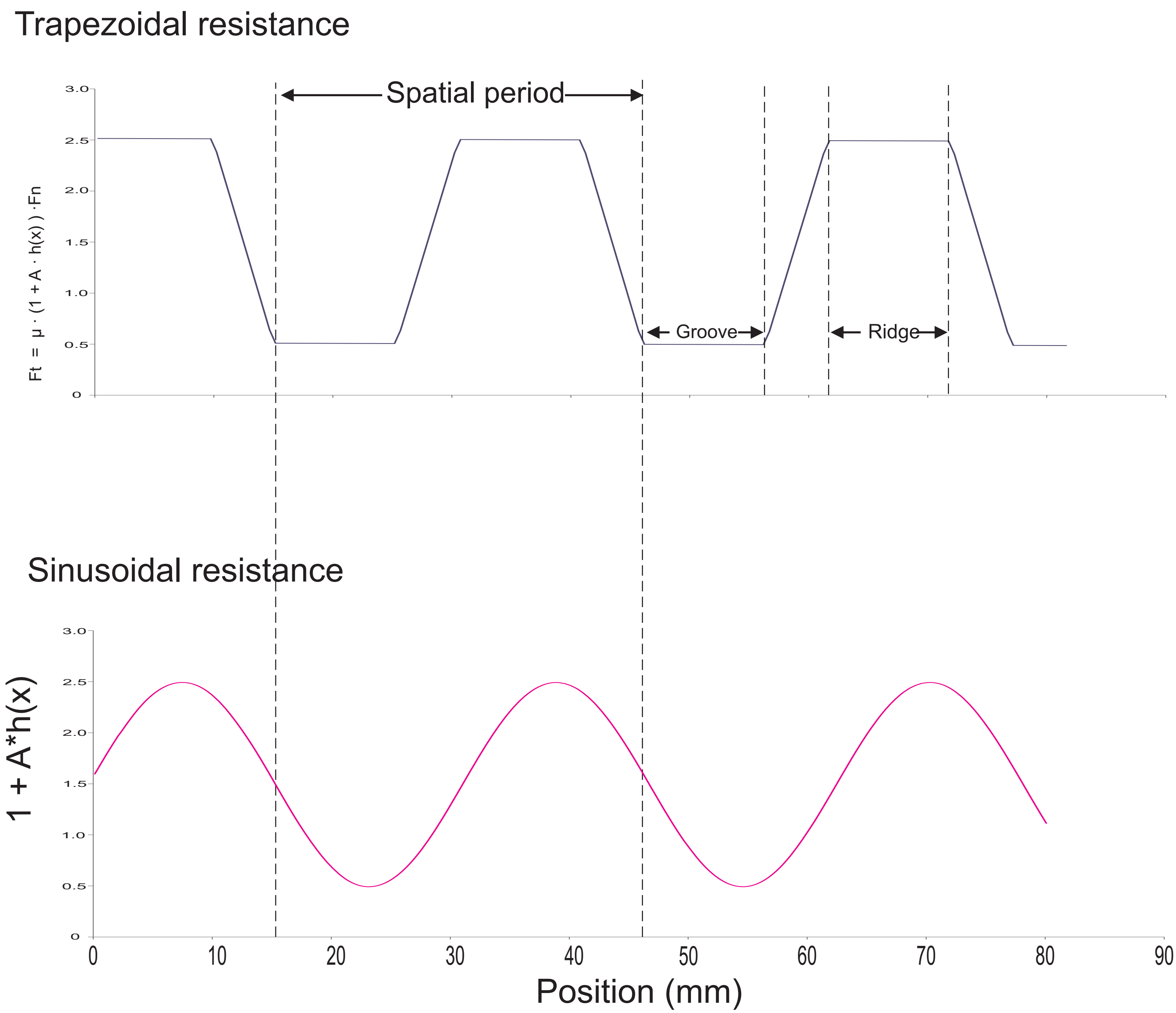

Figure 3

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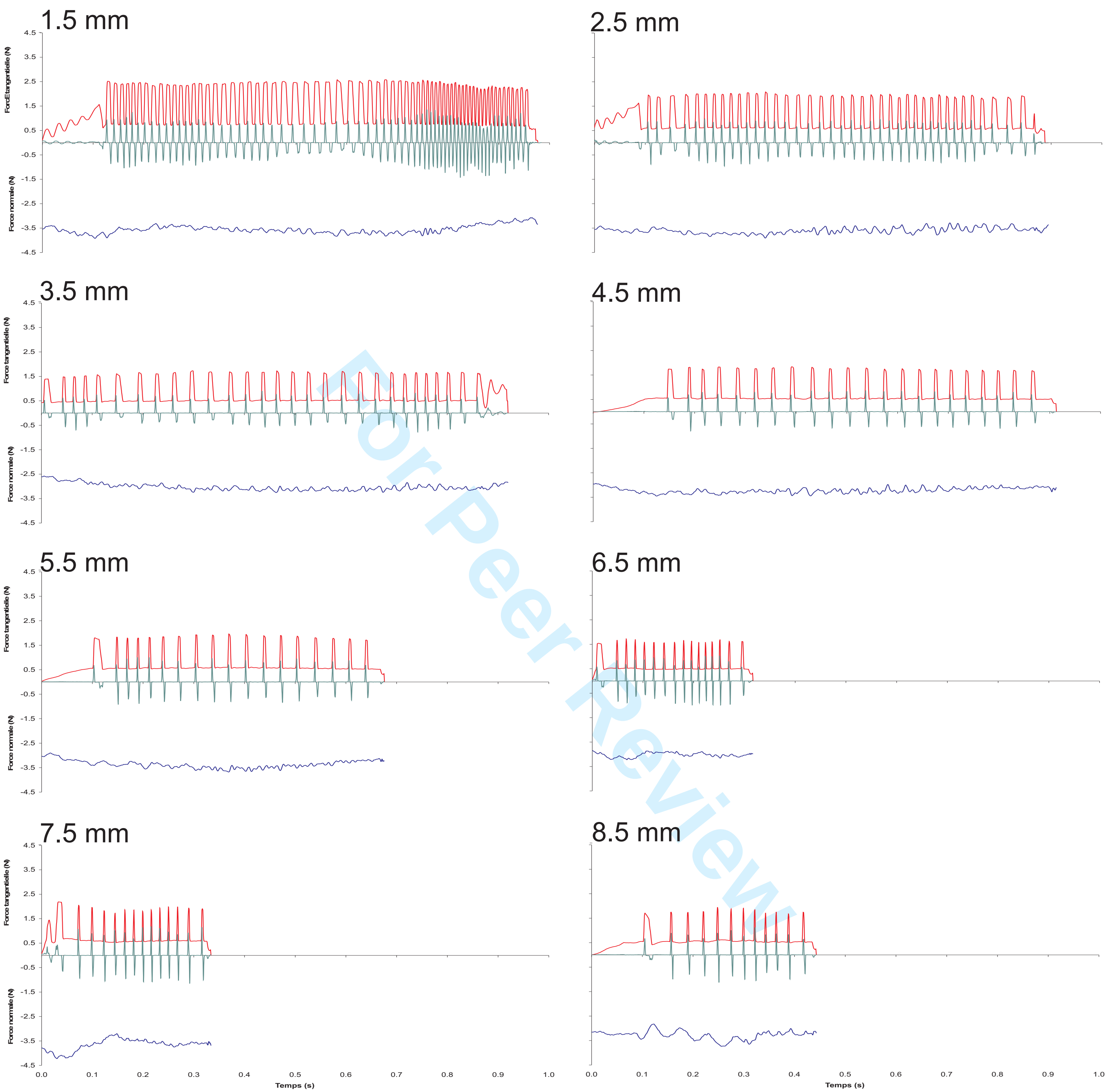

Figure 4

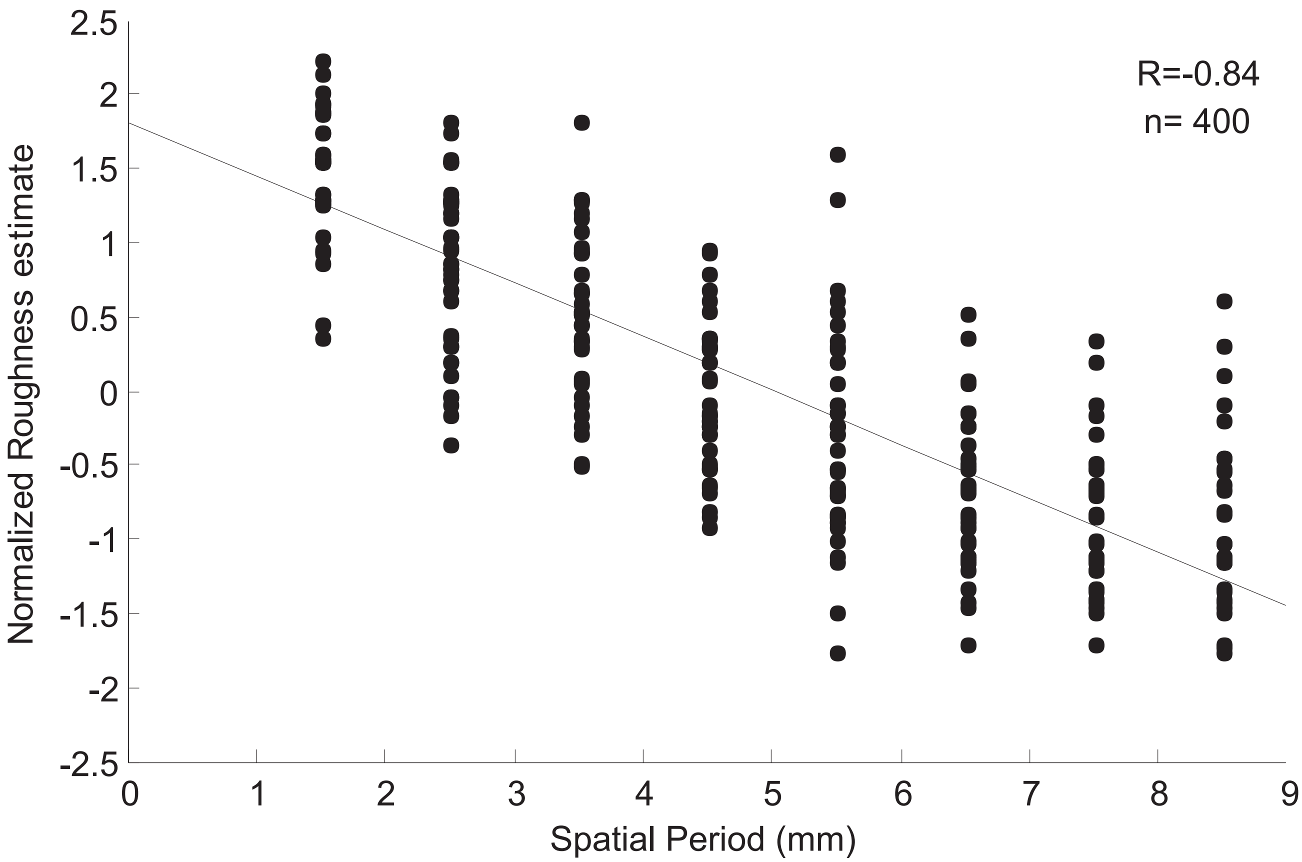
R=-0.84
n= 400
Normalized Roughness estimate
Spatial Period (mm)
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
0
1
2
3
4
5
6
7
8
9

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Figure 5

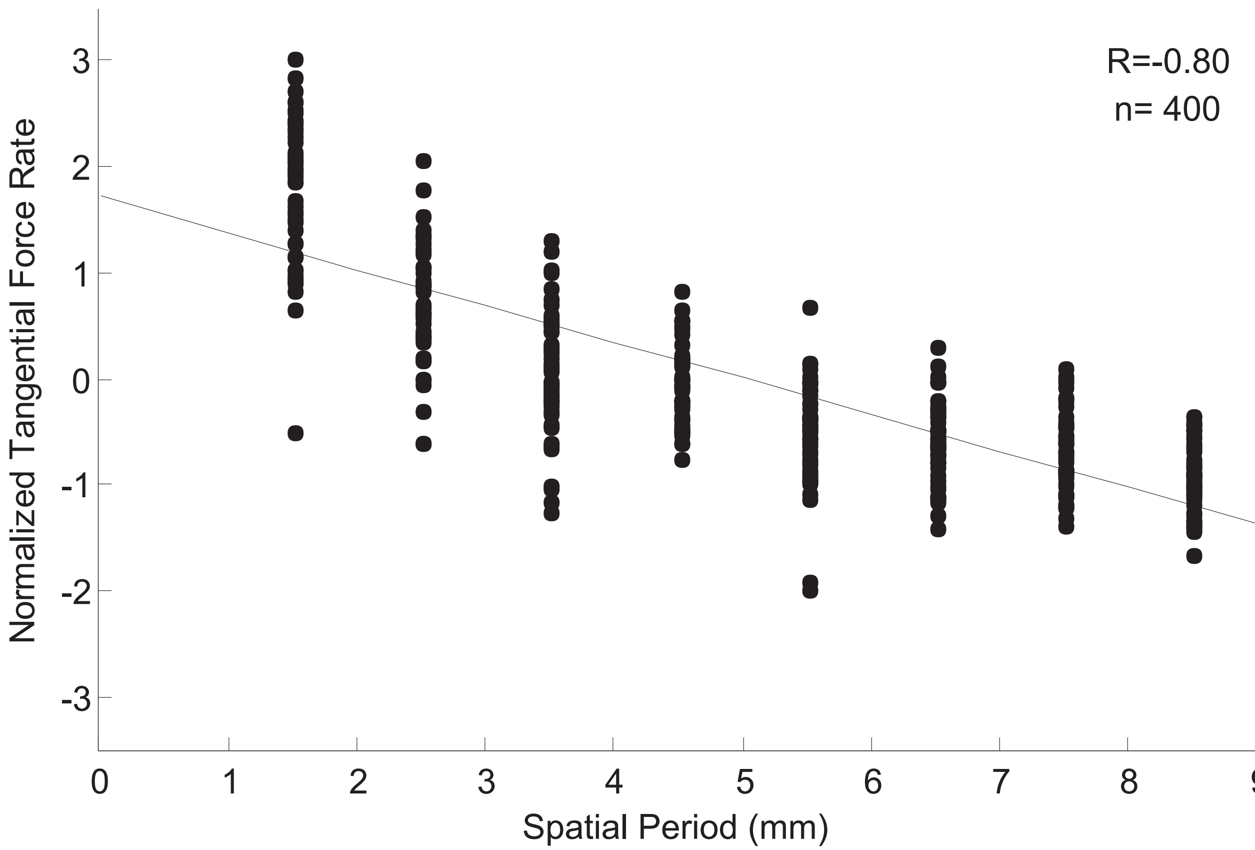

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Figure 6

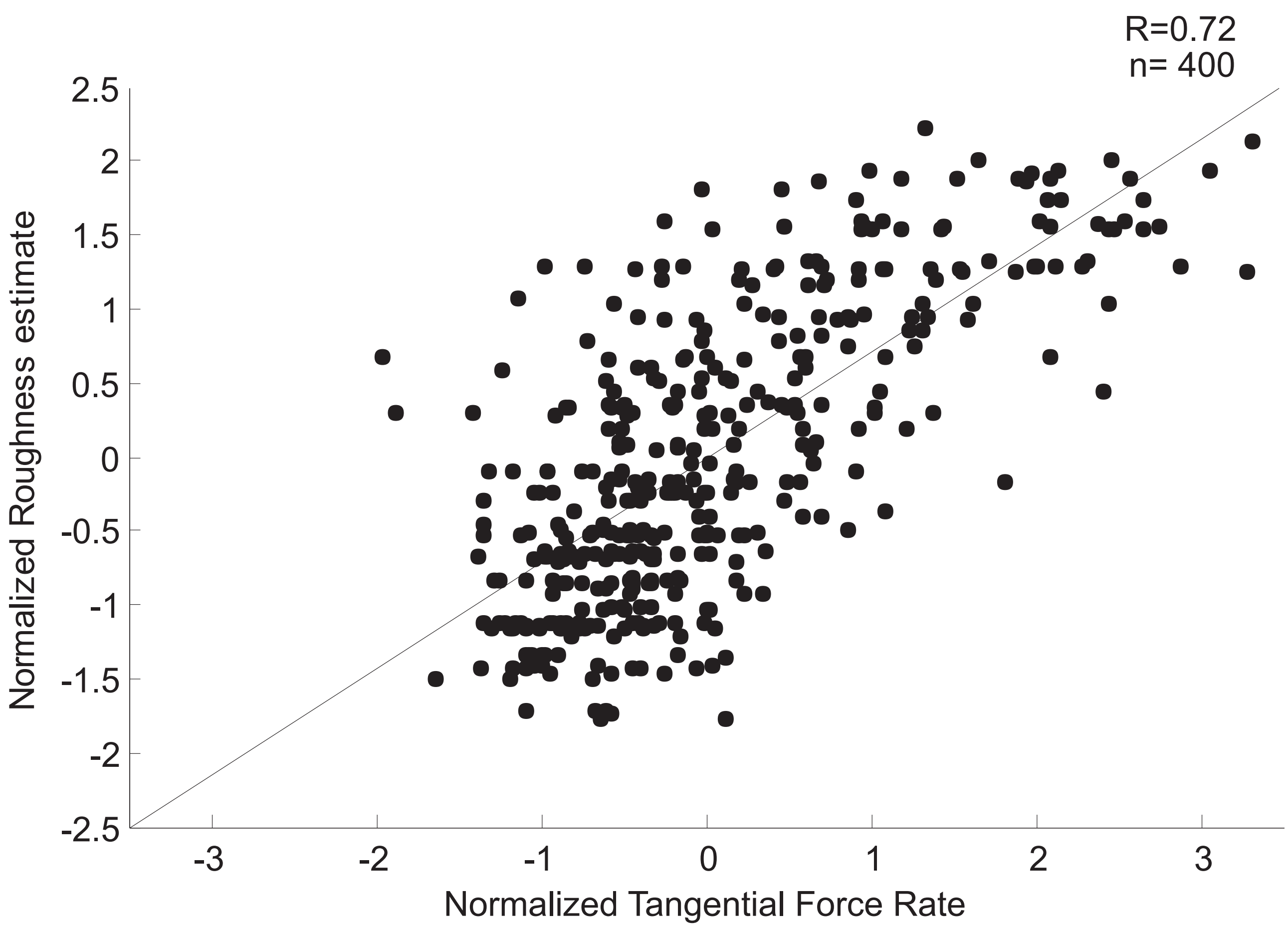

Figure 7

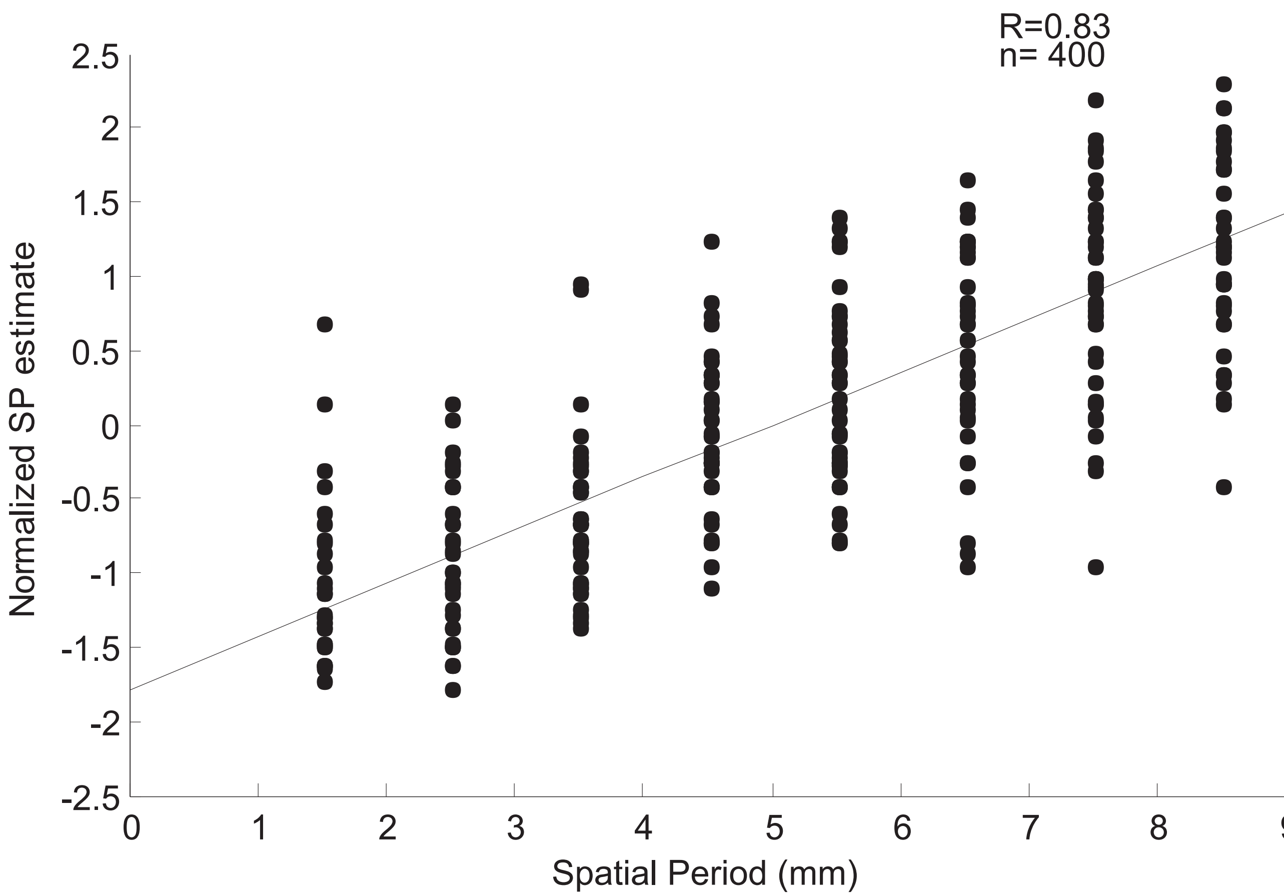
R=0.83
n= 400
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
Normalized SP estimate
0
1
2
3
4
5
6
7
8
9
Spatial Period (mm)

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Figure 8

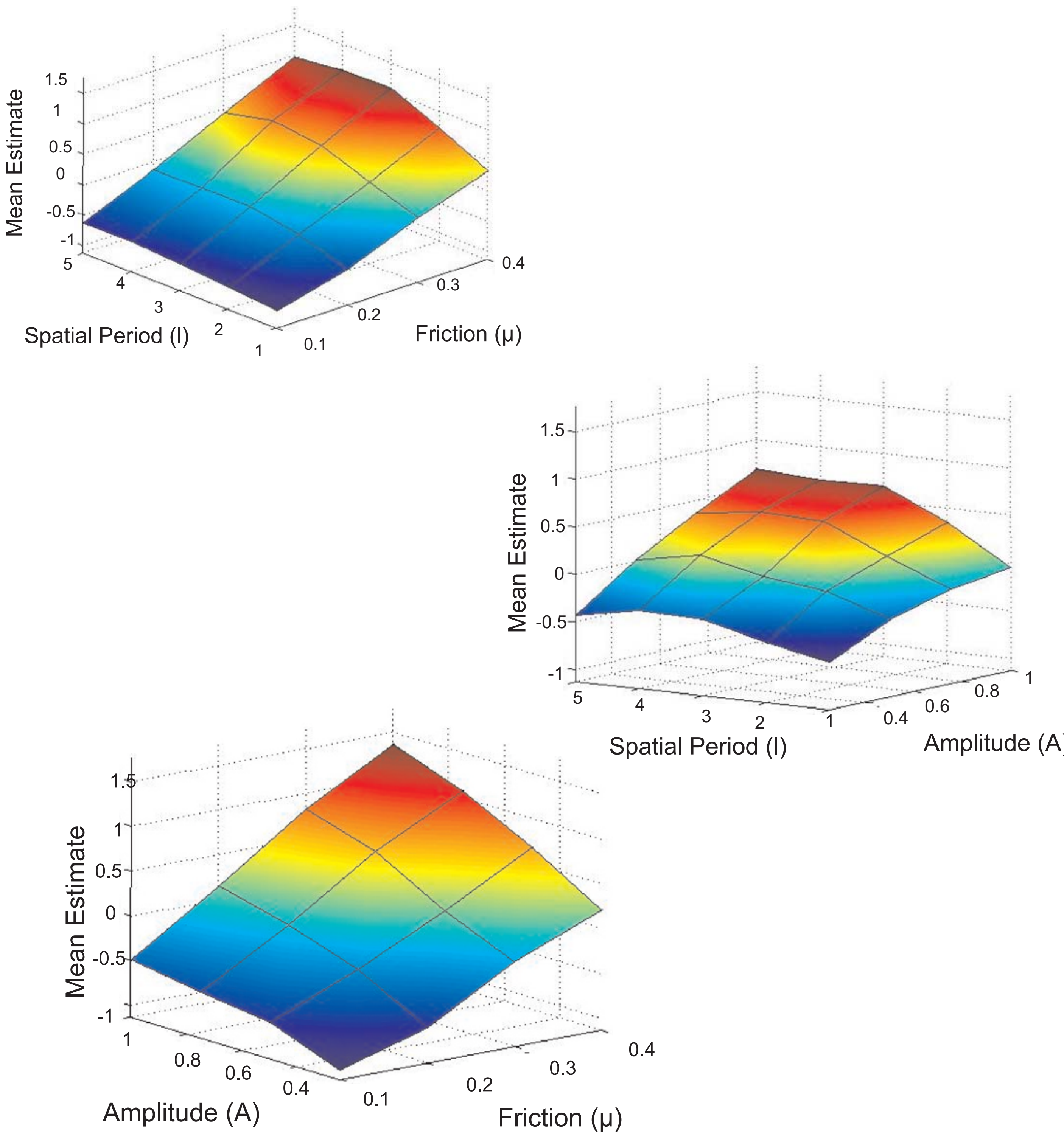

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Figure 9