Scale Dependence of Force Patterns During the Scanning of a Surface by a Bare Finger

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Abstract. This study investigated how the geometry of a touched surface influences forces felt during the scanning of an object with the finger. Although prior research, and basic mechanical considerations, have shed light on force production during haptic interaction with a touched object, surprisingly little is known about how to relate surface detail at different scales to the specific patterns of force that are observed. To address this, we designed an apparatus that could accurately measure normal and tangential forces between a finger and a surface. We fabricated sinusoidal surfaces with precisely controlled geometry, and measured spatial variations in resultant forces generated while subjects repeatedly scanned the surfaces at specified speed and pressure. Subsequent analysis revealed that the resulting force patterns varied in an organized way with spatial scale, and that fluctuations, in the form of aperiodic signal components that proved difficult to model, played an increasingly important role as the spatial scale of the surface geometry decreased. The results may help to explain differences in how surface detail is recovered by the haptic perceptual system at different length scales.

Keywords: Haptics, texture, vibration, finger, system identification

1 Introduction

There are many variables that affect the mechanical stimuli that underlie the sense of touch. A finger moving over an object experiences normal and tangential forces, and even torques, that depend on the structure, geometry and material properties of the touched object. These signals manifest themselves at a variety of length and time scales. Reproducing the full range of force and displacement stimuli felt by the hand during palpation is a long term goal of haptic engineering, but, to date, we have, at best, a limited understanding of what these stimuli are.

It has been observed that the production of forces by a sliding finger can be more readily interpreted in the spatial domain [1]. Basic contact mechanics can be sufficient to predict average forces as the finger slides across features that are large compared to its width [2], but the prediction of such forces when the geometric scale is smaller than the size of the finger remains daunting, and even at larger scales, fluctuations are difficult to account for. Prior research has shed some light on the interaction between tribological factors associated with scanning a surface with a synthetic fingertip [3], but the characterization and prediction of interaction forces involving a real finger have received limited attention. Several approaches to rendering force or acceleration information from surface measurements have been developed [4], Such measurement-based rendering algorithms are capable of realizing plausibly realistic interactions with diverse textured objects. However, there is little published work on predicting texture-induced forces felt by the bare finger [5]. In addition, measurement-based rendering algorithms are of limited utility in predicting forces that would be produced by a previously unexplored surface. Physically-motivated approaches to rendering forces produced during the scanning of virtual surface geometries can yield highly evocative experiences [6], but fall short of perceptual realism and physical accuracy.

Within the field of tribology, force production during frictional sliding and the identification of friction models have been extensively explored [7], but this work has been primarily concerned with the interaction between solid, machined surfaces. The complex morphology, and highly viscoelastic nature of the fingertip precludes the use of such models for analyzing or predicting finger-generated forces, although the system identification methods we investigated here are inspired by those used in the aforementioned studies.

The study presented here is motivated by the question of whether the spatial pattern of forces produced during the sliding of a finger on a structured surface can be predicted from knowledge of the geometry of the surface itself. We assumed that such a prediction should necessarily depend on a number of factors, most notably: the dynamics of the finger, and the interfacial contact mechanics between the finger and the surface, on surface properties, and on interaction parameters including normal force and scanning speed. A long term aim of this research would be to further explain how a model for force production from a sliding finger may be structurally interpreted in terms of the former three factors, and may be inferred to vary with the latter two.

As a first step in this direction, we engineered a sensing instrument that allowed us to accurately measure contact forces and kinematics of a finger sliding on a structured surface with high dynamic range and temporal sensitivity. We fabricated surfaces of precisely known sinusoidal geometry, and recorded the interactions performed by several participants at specified normal force and scanning speed. We analyzed the resulting force patterns in the spatial domain, and related these spatial force patterns, and their variations between trials, to the surface geometry itself. In a further step, we estimated deterministic but nonlinear contact force models that could predict, to varying levels of accuracy, the mean force pattern that resulted from a given surface geometry. The results indicate that it is possible to predict mean interaction force patterns from geometry when the spatial scale of the surface geometry is sufficiently long, but that at smaller scales other physical processes that proved difficult to model dominated force production. The results have implications for the haptic simulation of surfaces and for the perceptual recovery of surface geometry via palpation.

2 Methods

We developed an apparatus and instrument for measuring mechanical interactions and kinematics of a fingertip sliding on a surface, fabricated surfaces with known geometry, consisting of sinusoidal gratings with different wavelengths, and measured force and kinematic data as individuals scanned the grating surfaces with their fingers. In order to extract invariant properties of these interactions, we analyzed these data in the spatial domain, and used system identification analyses to build predictive models for the generation of motion-dependent forces during surface exploration.

2.1 Measurement Apparatus

The apparatus (Fig. 1) consists of a multi-axis load cell designed to capture forces applied by a finger to its surface independent of the position at which they were applied, by measuring strain in the normal (vertical) direction at two locations, and tangential strain in the horizontal direction. The load cell was fabricated from type 6010 aluminum alloy using precise electrical discharge machining. The three force components were measured with three full-bridge strain gauges, bonded at the locations shown. The output of each strain gauge was amplified by an AD8429 low-noise instrumentation amplifier. The gain of each amplifier was 1000, and the measurement frequency bandwidth was 100 kHz. Structural resonances limit the usable bandwidth to a few hundred Hz, which, after digital correction of the frequency response in the band of interest (compensating effects of a resonance at 130 Hz), was sufficient for this study. The signal from each instrumentation amplifier was digitized (0.1 ms sample period, 16 bits) via a data acquisition device (USB-6009, National Instruments Inc., Austin, TX). Finger kinematic trajectories were captured using an optical motion capture system (Natural Point, Corvallis, OR) with a sampling period of 8.3 ms and an approximate spatial resolution of 0.2 mm.

Force calibration At each time instant, the apparatus measures force and position corresponding to an effective point load $\boldsymbol{F} = (F_N, F_T)$, where F_N and F_T are normal and tangential force components, applied at a position x. In order to translate measured voltage to force, we calibrated the device by applying standardized normal and tangential loads at an array of points on the measurement surface, and recording output voltage. The force-voltage relations proved highly linear, so that a minimum least squares linear fit could be used to compute force from voltage. The sum of outputs from strain sensors for normal (resp. tangential) directions proved sufficiently constant that we were able to accurately estimate force independent of the location at which a load was applied.

Surface profile stimuli We fabricated relief surfaces with known geometry, specified as height functions $h(x)$ that varied in a single dimension, in order to study the variation of forces with geometry during scanning of the surface with

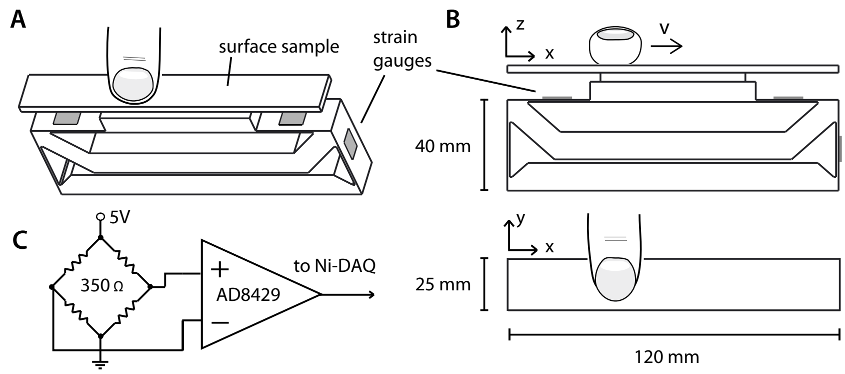

Fig. 1. A, B The measurement apparatus used in the experiment. Isometric view of the masurement apparatus. **C.** Simplified schematic of the strain gauge amplification circuit.

a finger. These surfaces were sinusoidal gratings with height profiles given by $h(x) = A\sin(2\pi x/\lambda)$, where amplitude A and spatial wavelength λ varied for each sample. Four such surfaces were used in our measurements, with $\lambda = 1$ mm, 2.5 mm, 3 mm and 4 mm (Fig. 2). Amplitude was equal to a fixed fraction of the wavelength for all samples, $A = 0.1\lambda$, ensuring that the maximum slope was constant for all samples – only the scale varied. The gratings were modeled parametrically and fabricated using a photopolymer resin 3D printer (maximum resolution 100 μm) yielding an artifact-free finish at the scales of interest (Objet 30, Stratasys Inc., Boston, USA). No further processing was used to modify the surface finish. The samples were firmly affixed to the force measurement apparatus with two-sided adhesive tape during the experiments.

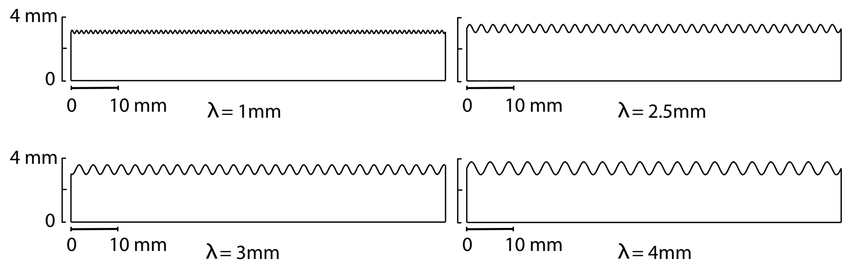

Fig. 2. Sinusoidal gratings used in the measurements differed only in spatial scale, λ.

2.2 Measurement procedure

During the measurements, the apparatus described above was used to capture normal forces, tangential forces, and finger position during scanning of the samples with the index finger. Three subjects (two male, one female, ages 20 to 33 years, all right hand dominant) volunteered to participate in the experiment. None evidenced any abnormality of biomechanics or function of the finger. Subjects were seated in front of the apparatus with the elbow supported and forearm held at a comfortable angle.

During each of five sets of trials, every subject scanned a surface 10 times in alternating directions with his or her index finger, yielding 50 scans per subject for each surface. Subjects were provided training and real-time feedback via a computer and graphical user interface that assisted them in maintaining constant normal force, and via an audio metronome that assisted them in maintaining a specified mean sliding speed ($v = 240$ mm/s), although we expected the realized velocity profiles to vary. The surfaces were cleaned after each set of trials with isopropyl alcohol.

2.3 Analysis of surface-dependent tangential force patterns

In our analysis, we focused on the tangential, frictional, force between the surface and finger. Following digitization, force and position data were resampled to a common rate of 10 kHz. Force data was band pass filtered to a range from 10 to 500 Hz using zero-phase filtering in order to remove variations due to low-frequency motor behavior and high-frequency artifacts from structural resonances. The synchronous force and position data were used to infer a spatial force pattern $\boldsymbol{F}(x)$ for each scan across the surface sample. We further limited our measurement range to the central 80 mm of the grating to eliminate edge effects.

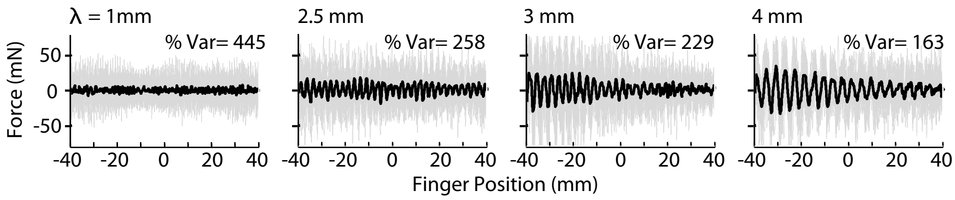

Fig. 3. The ensemble of patterns of tangential force components representing all trials from a single subject repeatedly scanning each sample. The black line displays the mean force pattern. The results clearly reflect the geometry of the underlying surface. The relative variation (%var) shown is the ratio of the standard deviation to the rms signal average. Its growth with decreasing λ decreases, evidence the relative increase in magnitude of fluctuations as scale decreases.

The force patterns for each participant, sample (wavelength), and scanning direction (left, right) were grouped for comparison (Fig. 3). For each grouping, the mean force pattern and variance were computed for further analysis. In order to compare with prior research on force production by sinusoidal surfaces, we analyzed spatial frequency content by computing a magnitude spectrum for each

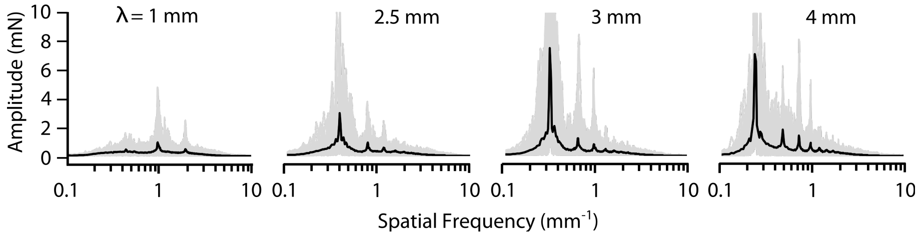

Fig. 4. Spatial spectrum (mean shown in black) for the tangential force of 75 trials for 3 subjects (25 trials per subject going right to left) scanning the 4 sinusodal gratings.

scan, using a Fourier transform in the spatial domain (Fig. 4). The results at all four scales evidence three main effects: a strong fundamental spatial period, corresponding to the surface wavelength λ, integer harmonic components, suggestive of a nonlinearity in the relation between surface height and tangential, and a $1/f$ trend of decreasing magnitude with frequency, consistent with prior literature on the spatial spectrum of forces during bare-finger contact [1].

2.4 Predictability of force production from surface geometry

Motivated by the extent to which force patterns $\boldsymbol{F}(x)$ seemed to reflect the underlying geometry $h(x)$, albeit in a possibly dynamical or nonlinear manner, we investigated the extent to which it is possible to predict these patterns given prior knowledge of $h(x)$. Since our goal was to determine whether prediction is possible, we deferred developing a specific model of mechanical interactions between the surface and a sliding finger, and instead used utilized powerful black box nonlinear system identification techniques to estimate optimal predictive models [8].

The models we estimated are generic nonlinear autoregressive processes expressed in the spatial domain with height $h(x) = u(x)$ as input and force $F_T(x) = y(x)$ as output. They are parametrized by linear autoregressive weight vectors A, B of order N, M and a nonlinearity G, in the form of a wavelet basis network with N_w kernels and N_r regressors; see Fig. 5, left panel. We adopted this model structure after extensive experimentation with alternatives. We optimized the models by performing a simultaneous grid search over the integer model order parameters N, M, N_w and N_r, and by maximizing the goodness-of-fit (GOF), between the measured data (y) and the estimated data from our model (ŷ), for a given model order, where

$$\text{GOF} = 100\% \times ||y - \hat{y}||/||y - \text{mean}(\hat{\text{y}})||$$

A total of 1600 candidate models were estimated at each wavelength λ, with 6400 models considered across all conditions. The optimal values of N and M lie between 2 and 10, and the optimal nonlinearity order N_w was between 8 and 18. There was no discernable pattern relating their values to λ. We used a training data set to estimate the models, and evaluated fit quality (Fig. 5) using separate testing data.

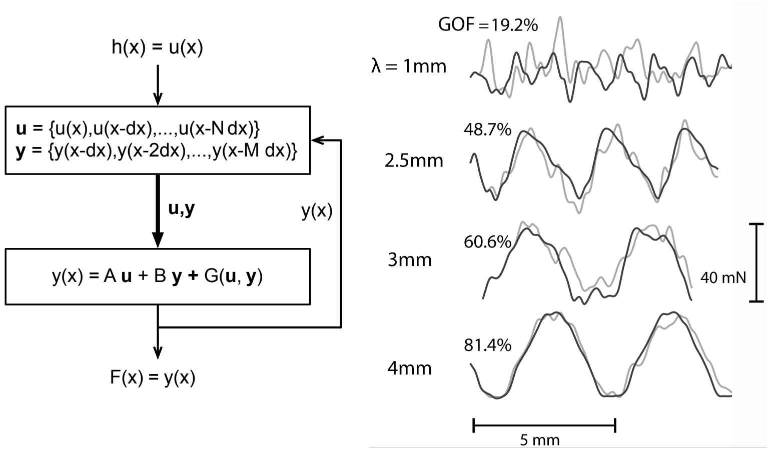

Fig. 5. Left: We investigated the use of geometry $h(x)$ to predict average tangential force patterns $F_T(x)$ by estimating nonlinear autoregressive system models in the spatial domain, with sample interval dx. Right: Optimal fit quality (%) at each scale λ over all models considered for previously unseen data, with sample model predictions (black line) and measurements (gray line). For large λ, accurate prediction is possible, but at short scales, force fluctuations are difficult to capture.

The results are summarized in Fig. 5. At the longest wavelength, the qualitative and quantitative correspondence is good, indicating that force data was well predicted by geometry. At shorter scales, no consistently predictive model could be determined, and many of the models in the search space failed to converge during estimation. At a scale of $\lambda = 1$ mm and at the exploration speed imposed here, the force patterns appear to be fundamentally difficult to predict, due to the presence of of aperiodic signal components that are, as noted above, large in relative magnitude and difficult to capture.

3 Conclusion

The forces that result from the scanning of a textured surface by a bare finger vary in a complex fashion as a function of surface geometry, even when other interaction parameters, such as normal force and scanning speed, are held constant. Nonetheless, this study revealed regularities in the correspondence between force and surface geometry that depend systematically on surface geometry $h(x)$. We demonstrated this by fabricating surfaces with known geometry $h(x)$ and by measuring force and position with high temporal and spatial resolution. The resulting forces exhibit quasi-regular fluctuations that we were partly successful in modeling as effects of the geometry of the surfaces. At spatial wavelengths greater than about 1 mm, we were successful in using nonlinear system identification techniques to predict observed forces from surface geometry. At short wavelengths, quasi-random force fluctuations became more important, with large variances that were readily observed in our measurements.

Despite the promising nature of this study, several open questions remain. Based on our experiment, it was not possible to definitively identify the origin of fluctuations that are observed at small wavelengths, but they could be due to a number of factors, including coupling to finger dynamics, finger ridges, the many surface contact patches involved, or to the presence of unstable stick-slip motion, or other unstable or chaotic modes of oscillation.

The nonlinear autoregressive models we employed are well suited to investigating the question of predictability of forces from geometry, which was our goal, but are of limited utility in supplying or suggesting mechanical interpretations for how these forces arise. In future work, we intend to further investigate the mechanical origin of finger-surface sliding forces, by relating a system model of force production to mechanical and geometric parameters. We also intend to relate finger surface forces to texture perception, in order to determine the extent to which different spatial signal components, including regular and irregular force components, contribute to surface perception. Finally, this study investigated force generation for a limited range of surfaces, and for a single material type, interaction speed, and normal force magnitude. In future work, we hope to explore the generalizability of these results to broader settings.

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